Impact of Electric Vehicles and Distributed Generation in Deregulated Power System

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Submitted by

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DECLARATION

I hereby declare that the research work presented in this thesis titled **"Impact of Electric Vehicles and Distributed Generation in Deregulated Power System"** submitted in partial fulfillment of the requirements for the award of degree of Doctor of Philosophy in the Department of Electrical & Instrumentation Engineering, Thapar Institute of Engineering & Technology, Patiala, is a bona-fide record of my own research work carried out under the supervision of Dr. Surya Prakash, Associate Professor, Electrical & Instrumentation Engineering, Thapar Institute of Engineering & Technology, Patiala.

The matter presented in this thesis has not been previously submitted in part or full to any other university or institution for the award of any degree in India or abroad.

Date : 15/1/2021

(Ankush Dutta)

I certify that the above statement made by the student is correct to the best of my knowledge and belief.

Date : 15/1/2021

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ABSTRACT

In recent years, integration of renewable sources in electrical grid and deregulation of electricity market has become inevitable. Use of renewable energy decreases consumption of fossil fuel and pollutant emissions. Deregulation of electricity market introduces competition in the electricity market which is beneficial for both suppliers and consumers. However, in a renewable energy integrated power system, there is severe frequency fluctuation due to the intermittent nature of the renewable sources and sometimes due to load changes. As frequency fluctuation is not at all desired for electrical utilities, it should be minimized using load frequency control (LFC) scheme.

In this work a LFC scheme incorporating Distributed Generation (DG) and Electric Vehicles (EVs) is proposed and implemented on multi-area deregulated hybrid power system (DHPS) having two different configurations. The salient feature of this work is that renewable energy sources (RESs) are made to participate in LFC along with proper choice of back-up sources to offset the intermittency. Configuration-1 of the power system comprises of three interconnected areas. Area-1 consists of a thermal, hydro and a solar-battery unit. Supercapacitor (SC) is also connected to this area while area-2 consists of thermal, hydro and fuel cell-aqua electrolyser unit. In area-3 biomass based Heavy Duty Gas Turbine (HDGT) and Diesel Engine Generator (DEG) contributes to power generation along with thermal and hydro generating units. To improve the LFC performance, combination of Thyristor Controlled Phase Shifter (TCPS) and SC (TCPS-SC unit) is integrated into the power system. The implementation of TCPS-SC unit arrests the initial fall in frequency as well as the tie-line power deviations after a sudden load disturbance. The performance of the developed DHPS model is investigated by using proportional-integral-derivative (PID) controller.

Configuration-2 of the power system consists of a two-area DHPS model. Area-1 consists of thermal, hydro and solar photovoltaic (PV). EVs are used to handle intermittency of solar power while area-2 consists of thermal, hydro and biomass based HDGT. To make it more realistic, effect of nonlinearity constraints and time delay in communication channel is also considered. The performance of the developed DHPS model is investigated by using PID, fractional-order PID (FOPID) and brain emotional learning based intelligent controller (BELBIC). Simulated results show the superiority of BELBIC controller over other controllers in handling various LFC issues.

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LIST OF SYMBOLS

f	System frequency
R	Governor speed regulation parameter
B	Frequency bias constant
T_g	Time constant of governor
T_t	Time constant of turbine
K_{ps}	Gain of power system
T_{ps}	Time constant of power system
T	Synchronizing coefficient of the tie-line
a	Ratio of rated power of pair of areas
T_w	Water time constant
K_p	Proportional gain of hydraulic PID governor
K_i	Integral gain of hydraulic PID governor
K_d	Derivative gain of hydraulic PID governor
K_{PV}	Gain of photovoltaic
T_{PV}	Time constant of photovoltaic
K_{BESS}	Gain of battery energy storage system
T_{BESS}	Time constant of battery energy storage system
K_{SC}	Gain of supercapacitor
T_{SC}	Time constant of supercapacitor
K_{TCPS}	Gain of thyristor controlled phase shifter
T_{TCPS}	Time constant of thyristor controlled phase shifter
K_{FC}	Gain of fuel cell
T_{FC}	Time constant of fuel cell
K_{AE}	Gain of aqua-electrolyzer
T_{AE}	Time constant of aqua-electrolyzer
K_{DEG}	Gain of diesel engine generator
T_{DEG}	Time constant of diesel engine generator
K_{EV}	Gain of electric vehicle
T_{EV}	Time constant of electric vehicle

LIST OF ABBREVIATIONS

ABC	Artificial Bee Colony
ACE	Area Control Error
ACO	Ant Colony Optimization
AE	Aqua Electrolyzer
AGC	Automatic Generation Control
ANN	Artificial Neural Network
BBBC	Big Bang Big Crunch
BELBIC	Brain Emotional Learning Based Intelligent Controller
BESS	Battery Energy Storage System
BFOA	Bacterial Foraging Optimization Algorithm
BIA	Bat Inspired Algorithm
BPA	Back Propogation Algorithm
CDM	Coefficient Diagram Method
CPS	Control Performance Standard
CS	Cuckoo Search
DE	Differential Evolution
DEG	Diesel Engine Generator
DFIG	Doubly fed Induction Generator
DG	Distributed Generation
DHPS	Deregulated Hybrid Power System
DISCO	Distribution Company
DOF	Degree of Freedom
DoS	Denial of Service
EC	Emotional Cue
ECO	Ecological Optimal Technique
EDLC	Electric Double Layer Capacitor
ESS	Energy Storage System
EV	Electric Vehicle
FA	Firefly Algorithm
FACTS	Flexible Alternating Current Transmission System
FC	Fuel Cell
FERC	Federal Energy Regulatory Commission

FIS	Fuzzy Inference System
FL	Fuzz Logic
FOMCON	Fractional-Order Modeling and Control
FOPID	Fractional-Order PID
GA	Genetic Algorithm
GDB	Governor Dead Band
GENCO	Generation Company
GHG	Greenhouse Gas
GRC	Generation Rate Constraint
GWO	Grey Wolf Optimization
HDGT	Heavy Duty Gas Turbine
HPSM	Hybrid Power System Model
HVDC	High Voltage Direct Current
ID	Integral Derivative
IPFC	Interline Power Flow Controller
ISDN	Islanding Smart Distribution Network
ISO	Independent System Operator
LFC	Load Frequency Control
LMI	Linear Matrix Inequalities
LQR	Linear Quadratic Regulator
LUS	Local Unimodal Sampling
MID	Modified Integral Derivative
MIMO	Multiple Input Multiple Output
MLPNN	Multilayer Perceptron Neural Network
MO	Model Output
MPPT	Maximum Power Point Tracking
OC	Orbitofrontal Cortex
PI	Proportional Integral
PID	Proportional Integral Derivative
PSO	Particle Swarm Optimization
PSS	Power System Stabilizer
PV	Photovoltaic
PWM	Pulse Width Modulation
RES	Renewable Energy Source

SA	Simulated Annealing
SC	Supercapacitor
SI	Sensory Input
SISO	Single Input Single Output
SMC	Sliding Mode Control
SMES	Superconducting Magnetic Energy Storage
SMO	Sliding Mode Observer
SOC	State of Charge
SSSC	Static Synchronous Series Compensator
SVC	Static Var Compensator
TBC	Tie-line Bias Control
TCPS	Thyristor Controlled Phase Shifter
TCSC	Thyristor Controlled Series Capacitor
TDMLP	Temporal Difference Learning Based Multilayer Perceptron
TDS	Time Delay Switch
TLBC	Transmission Line Bias Control
TLBO	Teaching Learning Based Optimization
TRANSCO	Transmission Company
TS	Tabu Search
UPFC	Unified Power Flow Controller
VSC	Variable Structure Control
WPH	Wolf Pack Hunting

CHAPTER 1
INTRODUCTION

1.1 Overview

Contribution of electrical energy in the growth of human race is boundless. As electrical energy can be generated in bulk amount and can be easily transmitted over long distances, it is the most favored and most extensively used form of energy. Normally bulk amount of electrical energy is generated by fossil fuel fired power plants. However, emission of particulates matter and other pollutants such as oxides of carbon, sulphur, nitrogen etc. due to burning of fossil fuel causes environmental degradation. With ever increasing energy demand, depleting fossil fuels, heightened environmental concerns, the concept of fossil fuel fired power plants for production of electrical energy is weakening. Therefore, utility generation paradigm is shifting from fossil fuel fired power plants to various small scale units which make use of small electric power generation resources located near its consumers and load centers. These generation resources are commonly known as DG resources which include, among others, wind energy, solar energy, diesel generator, fuel cells and energy storage systems (ESSs). But the intermittent behavior of RESs like solar, wind adversely affects the frequency of the power system. In order to ensure the generation and distribution of electric power with good quality the deviation of frequency has to be corrected. This is achieved by LFC also known as Automatic Generation Control (AGC) [1-3]. LFC is of utmost importance in hybrid (conventional + DG) power systems [4-7] as the deviations in load demand and stochastic nature of solar, wind adversely affects the frequency of the power system. For the stable operation of the power system, frequency is required to be maintained within permissible limits. Thus, for the enhanced and successful power system operation integrating RESs, backup in the form of energy storage is required as the operation of energy storage can balance the stochastic nature of the RES based generation. The battery storage of EVs has come up with an emerging thought which can perform as a backup to the alteration in power supply [8]. When hybrid with the DGs it comes up with a new promising option for today’s world growing demand. EVs are highly expected to meet the future energy demands.

The transport sector is also one of the major sources of air pollution. Road transport, in particular was considered responsible for more than 80% of the greenhouse gas (GHG) emissions from the transport sector as observed in Figure 1.1 [9].

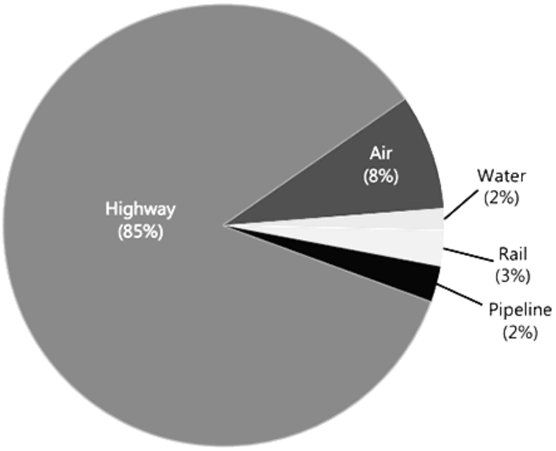


Figure 1.1: GHG emissions from various transport modes

CO_2 is one of the major greenhouse gases that adversely affect the environment. Share of various GHGs can be observed in Figure 1.2 [10].

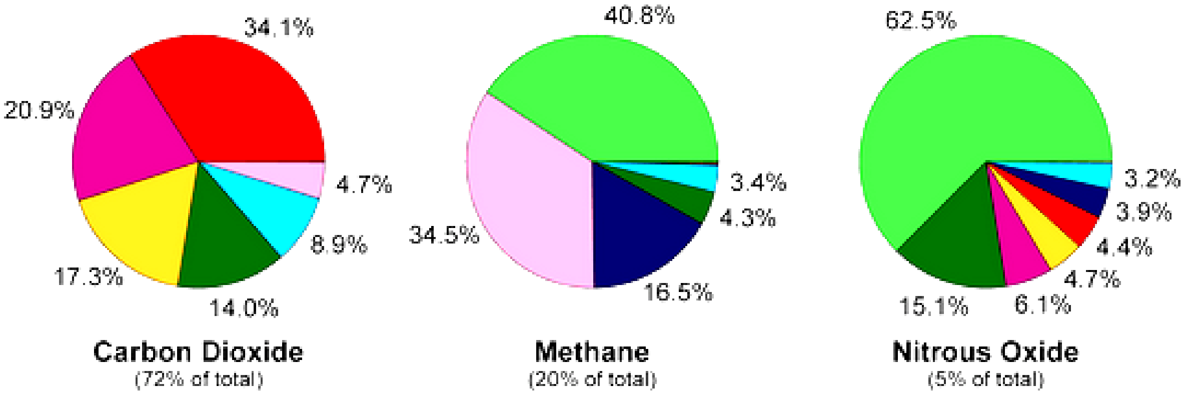


Figure 1.2: Primary Greenhouse Gases

But with the advent of EVs there is a considerable reduction in GHG emissions, thus providing opportunities for decarbonisation and making the environment pollution free. EVs together with RESs provide sustainable mobility [11].

Recent advances in power electronics have led to the development of the Flexible Alternating Current Transmission System (FACTS). FACTS devices [12] are designed to overcome the constraints of the present mechanically controlled power systems and increase power system stability by using steady and high-speed electronic devices. FACTS technology opens up space for controlling power and increasing the usable capacity of present, new and upgraded lines. These opportunities arise through the ability of FACTS devices to control the related parameters that control the operation of transmission systems including series impedance, shunt impedance, current, voltage, phase angle.

With the variation in the load demand on a generating unit, there is a momentarily occurrence of unbalance between real power input and output. To compensate this power imbalance, an ESS unit is incorporated in the power system [13]. Frequency oscillations due to large load disturbance can be effectively damped by fast acting energy storage devices.

In order to benefit consumers and power generating agencies, vertically integrated power systems structures are being replaced by deregulated power system worldwide. Though the basic mechanism of LFC remains same in both regulated and deregulated environment, there exist some other additional factors in deregulated environment [14,15].

As modern interconnected power systems are very large, manual regulation is not a realistic approach. Hence, all most all power generating systems are equipped with AGC scheme. The system performance is improved through proper tuning of controllers for a specific operating condition. In an interconnected power system controllers operate to adjust tie-line power flow. In fact, the deviation in frequency and change in tie line power flow directs the operation of controller.

1.2 Importance of Load Frequency Control

Frequent occurring voltage spikes and sags, frequency deviations, presence of harmonics etc. affects power quality adversely and reduces the life expectancy of electrical equipments. With abrupt change in load demand, frequency deviates from its nominal value. This change in frequency is highly undesirable and it should be minimized to zero immediately. Maximum permissible change in power frequency is ±0.05 Hz.

Various methods like Flat frequency regulation, Parallel frequency regulation; Selective frequency control, Tie-line load bias control etc. are available for maintaining constant system frequency [1]. Out of all these methods tie-line load bias control is the most popular method for LFC. In this method power system of every area of an interconnected system participate in frequency regulation regardless of the area in which frequency change was first originated [1]. Tie-line load frequency controller utilizes a master load frequency controller and a tie-line recorder which measures the power flow on the tie-line. The tie- line data drives the load frequency controller until the desired system frequency is restored.

1.3 Aim of Research

LFC being the most important aspect of power system operation and control has evolved with time. A hybrid power system comprising RESs is much susceptible to frequency fluctuation due to the intermittent nature of such kind of energy resources. Hence LFC must be used to combat the situation. Again in a restructured power system, LFC has to be further modified to incorporate different type of transactions between generation and distribution companies. Proper choice of controllers and use of ESS, FACTS devices can effectively solve the LFC problem.

The aim of this thesis is to carry out LFC of a multi-area DHPS integrating DG sources and EVs in the power system. For this vary purpose, two different power system configurations are considered. In configuration-1, a three-area DHPS is considered which consists of various DG sources like solar PV, fuel cell (FC), biomass based HDGT, DEG integrated with the conventional thermal, hydro generating units. Battery energy storage system (BESS) is used with solar PV and Aqua-electrolyser (AE) is used to generate hydrogen which is necessary to drive fuel cell. Biomass based HDGT and DEG also contributes to power generation along with conventional generating units. To improve the LFC performance, TCPS-SC unit is included in the power system. The performance of the developed DHPS model is investigated by using PID controller.

Configuration-2 of the power system comprises of a two-area DHPS model consisting of DG sources like solar PV and biomass based HDGT. EVs are used to handle intermittency of solar power. To make it more realistic, effect of nonlinearity constraints and time delay in communication channel is also considered. The performance of the developed DHPS model is investigated by using different controllers. Comparative results of various controllers in terms of settling time and peak over/undershoot are presented. Sensitivity analysis is carried out to check the robustness of controllers.

1.4 Research Objectives

1) To develop the model of deregulated power system.
2) To incorporate electric vehicles and distributed generation sources in deregulated power system for frequency support.
3) To incorporate energy storage system and FACTS devices in proposed system.
4) To investigate the performance of the developed model with the designed controllers.

1.5 Proposed Work

In this dissertation LFC of multi-area DHPS is proposed. This is achieved by considering two different power system configurations comprising of solar PV, FC, DEG and biomass based HDGT along with conventional thermal and hydro generating units.

Configuration-1 comprises of a three-area DHPS consisting of various DG sources like solar PV, FC, biomass based HDGT, DEG. Battery energy storage system (BESS) is used with solar PV and Aqua-electrolyser (AE) is used to generate hydrogen which is necessary to drive fuel cell. Biomass based HDGT and DEG also contributes to power generation along with conventional generating units. To improve the LFC performance, TCPS-SC unit is included in the power system. The performance of the developed DHPS model is investigated by using PID controller.

Configuration-2 of the power system comprises of a two-area DHPS model consisting of DG sources like solar PV and biomass based HDGT. EVs are used to handle intermittency of solar power. To make it more realistic, effect of nonlinearity constraints and time delay in communication channel is also considered. The performance of the developed DHPS model is investigated by using different controllers. Comparative results of various controllers in terms of settling time and peak over/undershoot are presented. Sensitivity analysis is carried out to check the robustness of controllers. The two different configurations of multi-area DHPS are developed in MATLAB/Simulink platform. For first time BELBIC controller is implemented for LFC of DHPS.

1.6 Contribution of Research Work

In the present work LFC of multi-area DHPS is carried out successfully by using two different power system configurations in deregulated environment. Multi-area DHPS model has been developed in MATLAB/Simulink. The contracts between various GENCOs and DISCOs are visualized using two different DPM’s. Various nonlinearity constraints GRC and GDB are taken into account. Time delay in communication channel is also considered. Every possible effort has been made to give a realistic view to the power system. Various DG sources like solar PV, FC, DEG and biomass based HDGT are made to participate in LFC phenomenon along with conventional thermal and hydro generating units. Random variations in renewable energy power source are also considered. BES of EVs is used to handle intermittency of solar power. AE produces hydrogen which is used by FC to produce energy. Biomass based HDGT is also considered for the generation of power. With ever increasing FACTS technology, TCPS has been used to reduce deviation in tie-line power and to increase system reliability. With use of SC along with TCPS has enormously increased the system performance. Coordinated action of TCPS-SC plays a great role in alleviating the LFC performance. Comparative results with and without integrating TCPS-SC combination is presented. The performance of the developed DHPS model is investigated by using various controllers like PID, FOPID and a new neuromorphic controller known as BELBIC. BELBIC is found to be more effective in diminishing frequency oscillations and also robust in handling system parameter variations and uncertainties. First time BELBIC is used for LFC of DHPS.

1.7 Organisation of Thesis

The thesis is organized in five chapters as follows:

Chapter 1 This chapter gives an overview of important LFC problem in hybrid power system and also discusses the role of DG sources and EVs in this important ancillary service (LFC). Role of FACTS and ESS is also discussed. The objectives and the contribution of the thesis have also been described in this chapter.

Chapter 2 An extensive literature survey on LFC problem is carried out in this chapter. The survey on LFC is classified on the basis of various distinct parameters. An effort has been made to study and summarize the work carried out by the researchers till date.

Chapter 3 This chapter discusses about the all the theories and concepts of LFC in deregulated power system with its equations and formulas. It also includes the theories and concepts of DG, V2G technology, FACTS and ESS with their modeling derivations and block diagrams. Theories and concepts of various controllers used are also presented along with their control equations.

Chapter 4 This chapter presents the dynamic frequency and tie-line power responses analyzed for different system conditions. It also includes the comparison of the responses obtained by simulating the LFC models with different controllers.

Chapter 5 This chapter presents the conclusion of the present work and future scope of work in LFC of DHPS.

CHAPTER 2
LITERATURE SURVEY

2.1 Overview

The AGC problem has been made of great value of research from time to time. AGC regulators have been developed to deal effectively with parametric uncertainties, incorporating area interconnections. In recent years, applications of genetic algorithm (GA), simulated annealing (SA), particle swarm optimization (PSO), ant colony optimization (ACO), fuzzy logic (FL), artificial neural network (ANN) and hybridization of these in the design of AGC regulators for interconnected power systems considering various types of model characteristics have also been witnessed in various articles [16]. A new artificial intelligent controller known as BELBIC has also been used for mitigating various LFC issues.

Apart from advances in AGC design techniques, there have been other developments during last two decades like; addition of RES and deregulation of power industries. These changes are posing new challenges for power engineers. For these reasons, the control schemes engaged with the AGC problem have changed to settle their dynamics appropriately. Broadly, AGC schemes based on various design techniques/methods can be categorized as: classical methods, optimal and suboptimal techniques, variable structure based methods, robust control methods, adaptive and self-tuning schemes, digital and discrete mode approaches and intelligent techniques [17-19]. AGC of a power system may be the initial idea implemented via flywheel governor of the synchronous machine. But this approach was found to be inadequate. Therefore, a secondary control was incorporated to the governor with the support of a signal directly proportional to the frequency deviation with its integral. This technique composes the classical approach to the AGC of power systems. Most of the research articles relating AGC of interconnected power systems are based on transmission line bias control (TLBC) method. The secondary AGC schemes are developed to control the area control errors (ACEs) to zero. The studies are largely carried out to put forward AGC regulator sketch patterns considering linear and non-linear power system models, centralized, decentralized, classical, optimal and sub-optimal control algorithms. The investigations also incorporate the sensitivity features, characteristics of load and excitation control in AGC approaches. The flow chart of the survey carried out for LFC is shown in Figure 2.1 below:

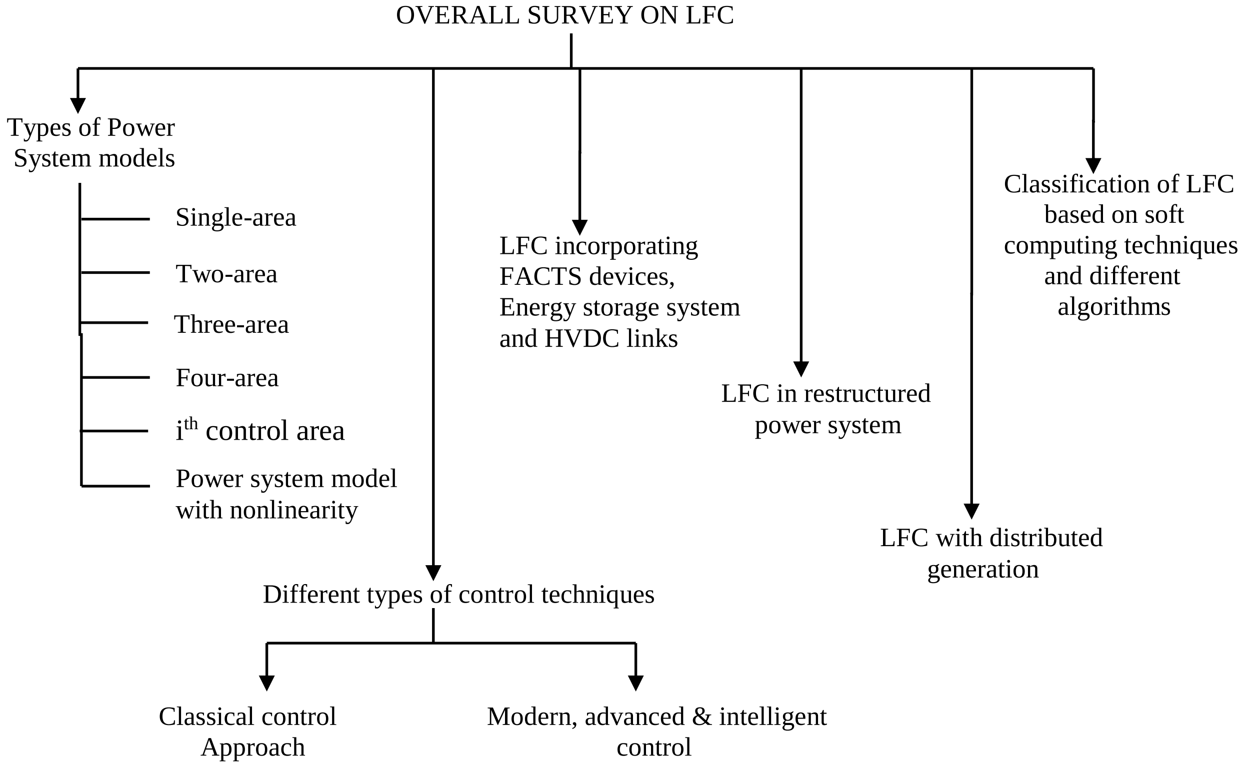


Figure 2.1: Flow Chart of Survey on LFC

2.2 Classification of LFC based on different types of power system models

The overall LFC mechanism in single-area power system is explained in [20–29] and a detailed investigation on single-area thermal power system incorporating LFC is presented in [20–26]. In [20] mathematical model mainly considering frequency controller of the power system is discussed. In [25] the LFC of multi-source system in a single-area is marked out. Single-area with only hydropower system is described in [27–29]. The LFC issues of two-area power system are efficiently highlighted in [30-37]. Concordia and Kirchmayer highlighted about tie-line power and frequency control of two-area power system in [30,31]. A model for two-area LFC system is developed with excitation control in one-area and voltage–perturbation in other area in [32]. In [33] reduction in two-area LFC model from 7th order to 2nd order with having same result as before is presented. In [34-36] a discussion about the regulation error of LFC of two-area power system is revealed and a sampled data of smart LFC based on the Lyapunov's second method is presented in [37]. Power systems incorporating three control areas are described by many researchers in [38–44]. In [38] a robust decentralized control for three-area system is presented. Bevrani et al. [39] presented an intelligent AGC based on Multi-agent Bayesian networks technique. In [40] three-area power system model with NARMA-L2 controller is investigated. A robust LFC controller for three-area system is described in [41,42]. In [43] LFC consisting of three-area system with adaptive fuzzy approach is presented. L. C. Saikia et al. [44] discussed about AGC of three-area hydrothermal system with neuro-fuzzy controller. The LFC demand in interconnected power system further increases to four control areas marked in [45-50]. In [51] LFC of a six-area hybrid multi-generation power system using Neuro-Fuzzy controller is presented.

A lot of research papers include the linear modeling of power systems which are different from the real time systems as real time systems are nonlinear in nature. This nonlinearity is added to the system model by implementing governor dead band (GDB) and generation rate constraint (GRC). [52–59] carries the LFC schemes for different areas with optimization based LFC of thermal reheat system and a non-linear control design which emphasized on GRC and GDB of the power system models.

2.3 Classification of LFC based on different control techniques

Classical controllers are the first stage closed loop controllers designed to overcome the limitations of open loop control system. A dual mode Proportional integral (PI) controller [60] and decentralized PI control [61] design for load frequency regulation with communication delays is presented. LFC of a PI based micro source system is also described [62]. In [63,64] Integral derivative (ID) controller for LFC is presented. A Modified integral derivative (MID) controller is proposed for LFC in deregulated environment [64]. LFC with PID controller for AGC of a two-area thermal system is presented in [65]. LFC with a unified PID tuning method is discussed in [66] and decentralized LFC using optimal Multiple input-Multiple output (MIMO) PID control is implemented in [67]. In [68] tuning of PID controller parameters using chaotic optimization algorithm for multi-area LFC is presented. R. K. Sahu et al. gives the idea of Differential evolution (DE) optimized parallel Two degree of freedom (2-DOF) PID controller for LFC with GDB nonlinearity [69]. In [70–74] authors presented LFC with PID controller in addition to different optimization techniques and algorithms. Optimal variation of frequency and voltage with PID and cuckoo search optimized PID controller is presented in [75]. Variable structure control (VSC) [76,77] is a well-known solution to the problem for the deterministic control of uncertain systems. Kwatny et al. [78] have presented a survey of application of optimal control theory for LFC. Ross [79] presented the adaptive control criteria. Pan and Liaw [80] proposed an adaptive controller including PI control technique and the effectiveness of the controller with GRC. In [81–

86] Sliding Mode Control (SMC) approach in the field of LFC is implemented. Application of Linear Matrix Inequalities (LMI) in the area of LFC of interconnected power system with communication time delays is presented in [87]. LFC with LMI is also presented in [88-90]. Artificial neural network (ANN) applied to LFC is presented in [91–95]. In [92] ANN is used as one of the two-loop controller for maximum power point tracking (MPPT). A robust and adaptive Temporal Difference Based MLP neural network for power system LFC is presented in [93]. A newly developed design strategy, which combines advantage of ANN and μ-synthesis control techniques for LFC is presented in [94]. Ansarian et al. [95] presented a new Linear quadratic regulator (LQR) solution, which is applied for a two-area power system using an ANN. A hybrid combination of ANN and Fuzzy is proposed as a controller for AGC problem in [51,96]. AGC with fuzzy control is presented in [97-105]. The fuzzy controller design, implementation and operation as part of the AGC system are discussed in [97-102]. Ghoshal and Goswami [103] highlighted the idea about scheduling of integral gains using GA based on fuzzy control. In [104] a multi-functional FL based Tie-line bias control (TBC) scheme considering the MWh constraint for the power transmission on the tie-line and the regulation margin is presented. Castro and Castillo [105] presented Interval Type-2 FL intelligent control for LFC. In [106] hysteresis current controlled three phase PWM converter using PI and Fuzzy is proposed. Binod et al. proposed a novel hybrid Local unimodal sampling (LUS) and Teaching learning based optimization (TLBO) based fuzzy-PID controller in [107].

In 2004, Lucas et al. introduced a new artificial intelligent controller based on medial brain model and emotional processes known as BELBIC [108,109]. BELBIC is a direct adaptive, model-free controller with low online computation, simple structure, and fast auto learning. It is very powerful in disturbance handling and robust with respect to parameter variations because of its appropriate learning ability. In [110], a self-tuning LFC strategy for microgrids has been proposed based on human brain emotional learning. BELBIC has been designed for velocity control of an electro hydraulic servo system, pitch control of helicopter, intelligent control of mechatronic systems, voltage tracking control of DC-DC boost converter, intelligent trajectory tracking control of unmanned aircraft systems, intelligent control system of mobile robots, distributed fault tolerant flocking control for multi-agent systems, intelligent flocking control for networked multi-unmanned aircraft system, to ameliorate small signal stability of interconnected hybrid power system in [111-119]. An efficient optimal fractional emotional intelligent controller has been proposed for an AVR System in Power Systems in [120], brain emotional learning-based intelligent decoupler has been proposed for nonlinear MIMO distillation columns in [121].

2.4 Classification of LFC based on application of FACTS devices, ESS, HVDC links

The implementation of FACTS devices in power system has become a universal enactment for making full utilization of existing transmission capacities. Emary and Shibina [122] proposed a novel LFC controller design which is based on Static Var Compensator (SVC). In [123] TCPS is applied to tie-line power flow of the interconnected hydrothermal power system. Applications of Thyristor Controlled Series Capacitor (TCSC), Static Synchronous Series Compensator (SSSC), Interline Power Flow Controller (IPFC) and Unified Power Flow Controller (UPFC) are highlighted in [124–130]. Bhatt et al. [131-133] explained the various combinations of energy storage devices and FACTS devices for mitigating the LFC issues in a conventional power system. Sahu et al. [126,128] explained about the application of IPFC and UPFC along with energy storage devices for controlling the various LFC issues in a deregulated power system. Load following service in a deregulated power system with TCSC is described in [134]. The two and three-area power systems with AC and DC tie-lines between power sectors are described in [135-141]. Chandrashekar et al. [135] explained the dynamic LFC analysis for a two-area deregulated power system with HVDC link in parallel with AC tie line. The two-area power systems interconnected via parallel AC/DC transmission links are described in [138]. Kumar et al. [136] present the design of Sliding Mode Observer (SMO) based controller (Local Load Frequency Controller) in a multi-area power system in coordination with HVDC link. The LFC of three-area power system containing one hydro and one thermal in each area and all these three areas are interconnected with HVDC link is described in [137]. LFC for a multi-area multi-source hydro-thermal power system interconnected via AC/DC parallel links under deregulated environment is discussed in [139]. LFC for three-area deregulated power system having AC tie-line parallel with HVDC link used as a system interconnection between all the control areas is explained in [142].Two-area power system having RESs, incorporating HVDC link is presented for LFC in [140,141,143].

2.5 LFC in restructured power system

Several studies are reported about various LFC issues of a two-area deregulated power system in [144–159]. Kothari et al. [144] explained the realistic AGC model for a two-area reheat thermal system under open market environment. LFC of a two-area deregulated multi-unit power system with each area having non-reheat thermal units [149,155,14,160-163] and reheat thermal units are discussed in [164-167]. LFC for a deregulated power system with hydro, reheat thermal and gas generating units type generating companies (GENCOs) are explained in [153,168,169]. LFC for a two-area deregulated power system having thermal reheaters and hydro units with GRC and without GRC are explained in [156,170-173]. LFC scheme for a two-area hydrothermal system consisting of mechanical and electric governor with GRC are explained in [156,174]. Two-area deregulated system with thermal reheat turbine and gas turbine coming under LFC applications is described in [159,139]. LFC for a three-area deregulated power system with hybrid turbines are explained in [175]. In this paper, a combination of Thermal-Thermal-Diesel, Thermal-Diesel-Hydro and Thermal-Thermal-Hydro with thermal units having reheat facility is analyzed. LFC for a three-area hydrothermal power system with and without GRC under three different contract scenarios are described in [176-181]. A combination of conventional and renewable GENCOs in a three-area system is presented in [182]. LFC problem for four- area deregulated power system with hydrothermal units are explained in [183-185]. Roy et al. [183] explained the LFC for a four-area system with different controllers. Federal Energy Regulatory Commission (FERC) regulations based four-area power systems having reheat thermal GENCOs are explained in [184]. The effects of boiler dynamics for thermal plant, GRC and GDB parameters in LFC are considered in [186]. LFC for five-area deregulated power system consisting of conventional and nonconventional generating units are discussed in [187,188]. Verma et al. [189] investigated the analysis of LFC of a two- area deregulated power system with doubly fed induction generators (DFIG) in both the control areas. Kirby et al. [190] describe the different methods of determining operating reserves for power systems with high penetrations of wind power. Rubin and Babcock [191] developed a theoretical framework model of deregulated electricity markets that explains two familiar empirical findings, viz. the existence of forward premiums and price-cost markups in the spot market. The short term active power support from DFIG with coordinated control of SSSC and Superconducting magnetic energy storage (SMES) in restructured power system is presented for LFC in [192].

2.6 LFC incorporated with DG

Detailed studies about hybrid power system model (HPSM) are reported in [193-203].

Kamwa et al. proposed the dynamic modeling and design of robust regulators for LFC in no-storage wind–diesel based HPSM [196]. Das et al. [195] conducted the dynamic analysis in terms of real power and LFC of an isolated PI/PID controlled wind–diesel based HPSM. Optimal LFC performances of different configurations of HPSM are examined with I, PI and PID controllers which are explained in [199]. Dynamic response of LFC in an isolated power system with and without BESS is presented in [197]. The design of load frequency controller by using coefficient diagram method (CDM) and ecological optimal technique (ECO) are described in [204]. AGC regulators using output feedback control strategy for a multi-area interconnected power system is proposed in [205]. Zeng et al. [206] developed a new optimization approach for active distribution system planning, which aims to effectively increase renewable energy usage in the unbundling market. Lei et al. [207] proposed a mixed homogeneous and heterogeneous multi-agent based wolf pack hunting (WPH) strategy for achieving the fastest LFC in an islanding smart distribution network (ISDN). Liu et al. [208] investigate the effects of Denial-of-Service (DoS) for LFC in smart grids. Communication time delay estimation for LFC in a two-area power system is explained in [209]. LFC strategies incorporating renewables are explained further in [210–221]. New LFC strategies for microgrids considering EVs are explained in [222-233]. An application of communication infrastructure based LFC in a multi-area smart grid power system is explained in [234]. Authors in [235] propose a time-delay-switch (TDS) attack by introducing time delays in the dynamics of smart grids power systems. A WPH strategy based virtual tribes control for AGC in a smart grid is described in [236]. In [237] the consequence of PV power generation on load frequency regulation is presented. A frequency control mechanism by PV generator in hybrid power system comprising PV and diesel generating units is explained in [238]. Datta et al. [239] revealed a coordinated control technique for power output variation leveling of PV system based on FL technique. Again in [240], a Minimal-order observer-based coordinated control method for isolated power utility of multiple PV systems is presented for LFC.

2.7 Classification of LFC based on soft computing techniques and different algorithms

ANN is an information processing paradigm, motivated from biological nervous system. The key element of this paradigm is the novel structure of the information processing system. It is composed of a large number of highly interconnected processing elements (neurons) working in unison to solve specific problems. An ANN is configured for a specific application, such as pattern recognition or data classification, through a learning process. The applications of neural networks for LFC issues are given in [241-248]. Modeling of a multilayer perceptron neural network (MLPNN) controller for three-area deregulated power system with reinforced learning was considered in [245]. A three layer feed forward neural network is proposed for controller design and trained with Back propagation algorithm (BPA) for a multi-area system having Poolco, bilateral and mixed transactions in [247,248]. Ram et al. [156] designed a FL controller using Mamdani and Sugeno type membership functions for LFC and its responses were compared with the classical integral controller in a deregulated power system. Shiva et al. [179] developed a fast acting Sugeno FL technique for on-line, off nominal operating conditions in a deregulated power system. The LFC problem using fuzzy gain scheduling of I, PI, PID controllers in a two-area interconnected power system with GRC are explained in [249]. Rana et al. [250] proposed a Polar Fuzzy Controller and employed in the two-area interconnected hydro-thermal power system. Also optimal integral and PID gains parameters are tuned by the FL controller which is explained in [171]. Application of GA particularly in the field of AGC is highlighted in [251-258]. In [252] a recognition procedure for a hydropower generating plant using an adaptive technique was investigated. A variable structure controller for LFC based on GA is proposed in [253]. A LFC controller based on fuzzy gain scheduling designed by a new GA technique is discussed in [252–258]. A new control technique based on robust GA for betterment of transient behavior of interconnected power system is presented in [259]. Implementation of PSO makes the design effort simple and improves the controller performances. Application of PSO in LFC is presented in [260-264]. PSO algorithm is applied to AGC for interconnected power grid in the CPS (Control Performance Standard) standard in [260,263]. In [264], three power system stabilizers (PSSs) applying the concept of PSO are developed and then these PSSs are installed together in the interconnected power system and their effect on its dynamic performance is studied. A study about operation of DE algorithm and its application to PI controller for AGC of an interconnected power system is explored in [265]. Fuzzy PID controller with Derivative filter is reflected for LFC in [266].

A parallel 2-DOF PID controller comprising DE for LFC of interconnected power system is presented in [69]. Implementation of the Firefly Algorithm (FA) with filtering technique based on wavelet transform is introduced for the purpose of removing noise(s) from the ACE signal in [267,268]. Ali and Abd-Elazim [269,270] presented a scheme of bacterial foraging optimization algorithm (BFOA) based PID controller for two-area power system with non-linearity. Stability enhancement in DG system with ABC technique is discussed in [271-273]. Bat inspired algorithm (BIA) is based on the echolocation behavior of micro bats with varying pulse rates of emission and loudness. AGC problems are solved using this algorithm in [274-276]. Cuckoo search (CS) is an optimization algorithm inspired by the obligate brood parasitism of some cuckoo species by laying their eggs in the nests of other host birds. In [277] comparison of different FACTS devices with application of cuckoo optimization technique is revealed. CS algorithm based load frequency controller for nonlinear interconnected power system is presented in [278]. Sharma and Lalit [279] proposed a Grey Wolf Optimization (GWO) algorithm based classical controllers. In [280] beta chaotic map enabled grey wolf optimizer is proposed. A multiple Tabu Search (TS) algorithm is proposed in [281]. A FOPID controller design using imperialist competitive algorithm & type-2 fuzzy PID using Big Bang Big Crunch (BBBC) optimization technique are investigated for LFC of interconnected power system in [282,283].

CHAPTER 3
MATERIALS AND METHODS

3.1 Concept of Deregulation

In earlier years, demand of electricity was less and essentially all power systems in operation were isolated power systems. In these conventional power systems a single utility company remains in control of generation, transmission and distribution of a certain area. In order to end this monopoly concept, deregulation was introduced. In a deregulated power system the vertically integrated structure of conventional power system is break up into three distinct independent utilities known as GENCOs (generation companies), TRANSCOs (Transmission companies) and DISCOs (distribution companies) which take care of generation, transmission and distribution respectively [15]. Each area consists of several GENCOs, DISCOs and TRANSCOs in a deregulated electricity market. Due to availability of various players in the market for generation, transmission and distribution there is a healthy competition that helps consumers.

3.1.1 Components of Deregulated Power System

In deregulated power system, generated power from producer to consumer is transmitted through three different utilities: GENCOs, TRANSCOs and DISCOs. Various components of a deregulated power system are briefly discussed below [15].

GENCOs: Generation companies are the first and foremost essential component of power industry. These utilities are the producer and seller of electrical energy. A generation company mainly consists of a single generating unit or a group of generating units.

TRANSCOs: The utilities which own and govern the transmission lines are known as TRANSCOs. Their main duty is to transport electrical energy generated by generation companies to distribution companies.

DISCOs: It refers to distribution companies which delivers electricity to the end users i.e. consumers after purchasing electricity through spot market or from GENCOs through direct contract. They own and operate the local distribution network.

Consumer: A consumer is an entity that consumes electricity [2]. Consumers have options to purchase electricity either through bidding procedure from spot market or from GENCOs/local distribution companies.

Market Operator: Market operator is an entity which governs the trading process in electricity market [2].

Independent System Operator (ISO): A central operator which governs and monitors whole system impartially is known as ISO. It handles the frequency control services, supplies energy reserves etc. It ensures system reliability and security. All the ancillary service including AGC remains under the control of ISO [2].

3.1.2 Benefits of Competitive Electricity Market

It is a well known fact that a competitive market is always beneficial for consumers. Some benefits of competitive electricity market are listed below [2].

i To sustain themselves in a competitive market generation companies are required to generate electrical energy in an efficient and economical way. This ensures up gradation of power production technologies.

Ii Similarly transmission and distribution companies are enforced to put reduction in transmission losses and to take care of power theft.

Iii A competitive market dispenses electrical energy at the best price that motivates different business agencies to invest in power industry.

Iv As consumers have numerous options for buying electricity, competition among the energy producers is tough, hence increasing service reliability.

3.1.3 Load Frequency Control of Deregulated Power System

In a deregulated power system, the engineering aspects of planning and operation of LFC is modified though the main concept remains same. As mentioned above an ISO coordinates the operation of all GENCOs, TRANSCOs and DISCOs in the system and monitors all ancillary services. Hence, while designing a LFC control scheme for a multi-area restructured power system all these things should be taken into consideration. Hence the relations between the GENCOs and DISCOs of the isolated or interconnected areas are needed to be defined through proper contracts made among them.

3.1.4 DISCO Participation Matrix (DPM)

In an open market scenario a DISCO is free to purchase power from any GENCO either in its own area or in other area according to its convenience. A contract between a GENCO of one area with DISCO of other area for purchase of power is known as “bilateral transaction” and should be approved by ISO. As there are multiple GENCOs and DISCOs in every area several combinations of GENCO-DISCO contracts are possible [15]. A DISCO participation matrix which is popularly known as DPM is used for representing a set of GENCO-DISCO contracts in the power system for the ease of visualization. Number of rows and column in a DPM is same as that of number of GENCOs and number of DISCOs in the system. The sloping (diagonal) elements of the DPM correspond to local demand and the off-diagonal elements represent demand from other areas [15].

3.1.5 Contract Participation Factor (cpf)

Each element of DPM is known as cpf that represents the fraction of total load demand of a DISCO committed by a GENCO. For example nth column element of mth row of a DPM i.e. cpf_{mn} denotes the fraction of total load demand of nth DISCO supplied by mth GENCO. Hence, sum of each column of DPM matrix should be unity [15].

$$\sum_m cpf_{mn} = 1 \qquad (3.1)$$

If there is an increase in demand by a DISCO, then contribution of each GENCO towards satisfying this incremental demand is proportional to its cpf. DPM of a power system with i number of GENCO and j number of DISCO can be given as [284]:

$$\text{DPM} = \begin{pmatrix} \text{cpf}_{11} & \text{——} & \text{cpf}_{1j} \\ \Big| & & .\ \Big| \\ \text{cpf}_{i1} & \text{——} & \text{cpf}_{ij} \end{pmatrix} \qquad (3.2)$$

3.1.6 Load Frequency Control of Two-Area Deregulated Power System

LFC of a two-area power system (Figure 3.1) interconnected by tie-line is described in this section. The objective of LFC of interconnected system is the same as that of the isolated power system. But due to the interconnection between different power systems, control of tie–line power flow is also considered along with the frequency regulation as per the contracts made between different GENCOs and DISCOs. The contracts made between various GENCOs and DISCOs are represented by the following DPM:

$$\text{DPM} = \begin{pmatrix} \text{cpf}_{11} & \text{cpf}_{12} & \text{cpf}_{13} & \text{cpf}_{14} \\ \text{cpf}_{21} & \text{cpf}_{22} & \text{cpf}_{23} & \text{cpf}_{24} \\ \text{cpf}_{31} & \text{cpf}_{32} & \text{cpf}_{33} & \text{cpf}_{34} \\ \text{cpf}_{41} & \text{cpf}_{42} & \text{cpf}_{43} & \text{cpf}_{44} \end{pmatrix} \qquad (3.3)$$

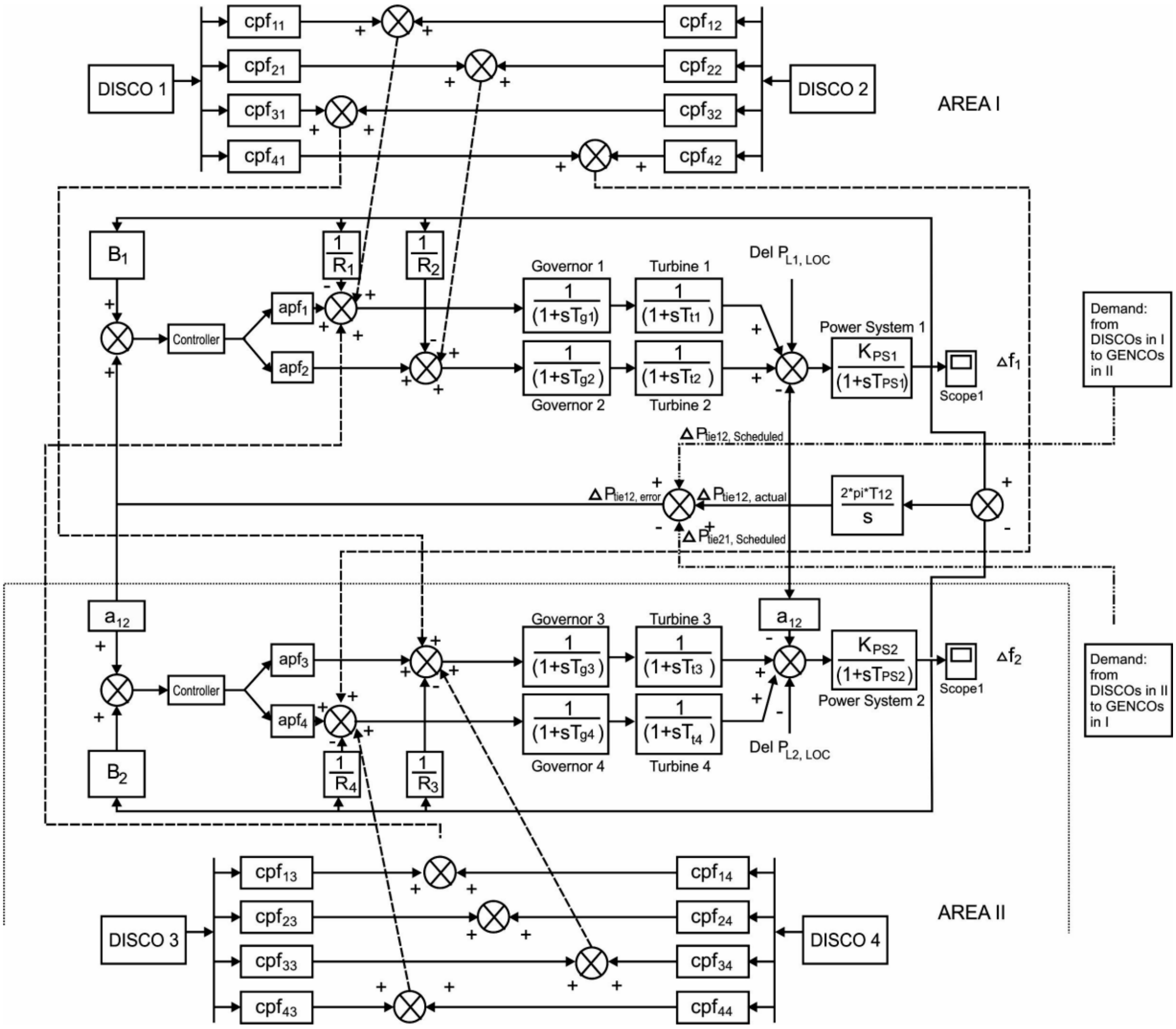


Figure 3.1: Block Diagram of Two-Area Deregulated Power System

Here a two-area power system is considered in which each area has two GENCOs and two DISCOs**.** The steady state tie-line power flow which is scheduled in a two-area system can be expressed [284] as:

$$\Delta P_{tie12,scheduled} = (\textit{Demand of DISCOs in area-2 from GENCOs in area-1 - Demand of DISCOs in area-1 from GENCOs in area-2}) \quad (3.4)$$

The actual steady state power flow on the tie line can be given as [2]:

$$\Delta P_{tie12,actual} = \left(\frac{2\pi T_{12}}{s}\right).(\Delta f_1 - \Delta f_2) \quad (3.5)$$

The tie-line power error is calculated as [2]:

$$\Delta P_{tie12,error} = \Delta P_{tie12,actual} - \Delta P_{tie12,scheduled} \quad (3.6)$$

$\Delta P_{tie12,error}$ reduces to zero [285], when steady state is reached.

For an isolated system if the system frequency changes then the primary frequency controller settles down the frequency deviation to zero. But for an interconnected power system there is also a change in tie–line power due to the frequency deviation. Hence, to settle down the tie–line deviation to its steady state value, another feedback signal from the tie–line is introduced in LFC for interconnected power system. ACE signals are formulated by using the tie line power error and can be expressed as [284]:

$$ACE_1 = B_1 \Delta f_1 + \Delta P_{tie12,error} \tag{3.7}$$

$$ACE_2 = B_2 \Delta f_2 + \Delta P_{tie21,error} \tag{3.8}$$

Since, in each area there are multiple GENCOs, ACE signal is also distributed among them in proportion to their participation in LFC. Coefficients those distribute ACE to the GENCOs are termed as “ACE Participation Factor‟ and is denoted by ‘apf’.

Contracted power supplied by ith GENCO is given as [2]:

$$\Delta P_{Gi} = \sum_i cpf_{ij} \Delta P_{Lj} \tag{3.9}$$

where ΔP_{Lj} refers to the total demand of DISCO$_j$.

Here, a two area system is considered so equation (3.9) can be written as:

$$\Delta P_1 = cpf_{11} \Delta P_{L1} + cpf_{12} \Delta P_{L2} + cpf_{13} \Delta P_{L3} + cpf_{14} \Delta P_{L4} \tag{3.10}$$

3.2 Distributed Generation (DG)

DG is an approach that employs small-scale technologies to produce electricity close to the end users of power [285-287]. DG technologies often consist of modular (and sometimes renewable-energy) generators, and they offer a number of potential benefits. In many cases, distributed generators can provide lower-cost electricity and higher power reliability and security with fewer environmental consequences than traditional power generators. DG systems employ numerous, but small plants and can provide power onsite with little dependence on the distribution and transmission grid. DG technologies yield power in capacities that range from a fraction of a kilowatt [kW] to about 100 megawatts [MW]. Utility-scale generation units generate power in capacities that often reach beyond 1,000 MW. DG takes place on two-levels: the local level and the end-point level. Local level power generation plants often include renewable energy technologies that are site specific, such as wind turbines, geothermal energy production, solar systems (photovoltaic and combustion) and some hydro-thermal plants. These plants tend to be smaller and less centralized than the traditional model plants. They also are frequently more energy and cost efficient and more reliable. Since these local level DG producers often take into account the local context, they usually produce less environment damaging or disrupting energy than the larger central model plants. At the end-point level the individual energy consumer can apply many of these same technologies with similar effects. One DG technology frequently employed by end-point users is the modular internal combustion engine.

Some of the DG technologies are listed below:

- Reciprocating Diesel or Natural Gas Engines
- Micro-Turbines
- Combustion Gas Turbines
- Fuel Cells
- Photovoltaic (PV) system
- Wind Turbines

Various applications, recent trends, benefits and challenges of DG are given in [288-292]. Table 3.1 [285] provides a brief overview of the most commonly used DG technologies and their typical module size.

Table 3.1: Various DG technologies with their module size

No.	Technology	Available module size
1	Combine Cycle Gas Turbine	35-400 *MW*
2	Internal Combustion Engines	5 *kW*-10 *MW*
3	Combustion Turbine	1-250 *MW*
4	Micro-Turbines	35 *kW*-1*MW*
5	Fuel Cells, Proton Exchange	1-250 *kW*
6	Battery Storage	0.5-5 *MW*
7	Small Hydro	1-100 *MW*
8	Wind Turbine	200 *W*-3 *MW*
9	Solar Thermal	1-10 *MW*
10	Biomass Gasification	100 *kW*-20 *MW*
11	Geothermal	5-100 *MW*
12	Ocean Energy	0.1-1 *MW*

DG includes the application of small generators scattered throughout a power system, to provide the electric power needed by electrical customers. Such locally distributed generation integrated to power system has several merits from the view point of environmental restriction and location limitations, as well as transient and voltage stability in the power system.

3.3 Vehicle-to-grid technology (V2G)

V2G describes a system in which plug-in electric vehicles such as electric cars i.e. battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs), communicate with the power grid to sell demand response services by either returning electricity to the grid or by controlling their charging rate [227-231]. Since at any given time 95 percent of cars are parked, the batteries in EVs could be used to let electricity flow from the car to the electric distribution network and back. Figure 3.2 represents the V2G system.

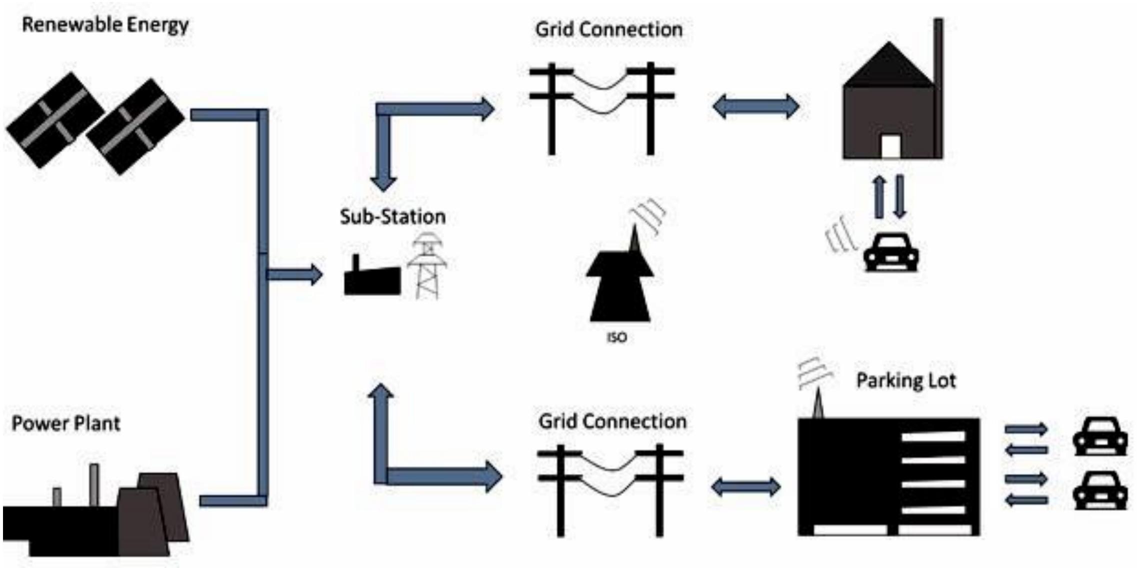


Figure 3.2: V2G System

The power generated from various sources such as RES (wind, solar, hydro) and thermal power plants flows in one direction into the system, and is distributed through the grid. This power is used to charge EVs at home, in the workplace, or at dedicated charging stations. The battery power of EVs is utilized to feed the system during peak electric demands, allowing a two-way flow system between the grid and the EV. The ISO functions as a central control system to facilitate communication between an EV and the grid. The ISO emits control signals in the form of broadcast radio signals, cell phone networks, or through power line carriers. The three basic requirements of the V2G technology are:

a) Power connection

b) Communication

c) Metering

EV is connected to the charging station and on-board power electronics to facilitate the bi-directional flow. Real-time communication is established between the vehicle and utility or the operator to provide control and management of power. A precise, temper free metering is very much required to accurately measure the power or services provided by the vehicles with its duration. V2G vehicles provide power to help balance loads by "valley filling" (charging at night when demand is low) and "peak shaving" (sending power back to the grid when demand is high).

3.4 Energy storage system (ESS)

Energy storage is the capture of energy produced at one time for use at a later time. ESS plays a significant role particularly in handling the intermittency of renewable. Although winds, solar are the important ones among the renewable sources, their intermittent power generation creates a limitation on their applications. To overcome this drawback storage systems are used. These storage systems acts as back up and eliminates the uncertainty in power supply to the load. LFC with application of storage unit makes renewable sources more reliable [168,197,198]. Various different types of ESS are listed below:

- Flywheel energy storage
- Pumped-storage
- Superconducting magnetic energy storage (SMES)
- Supercapacitor (SC)
- Battery Energy Storage (BES)
- Hydrogen Storage

3.5 Flexible Alternating Current Transmission System (FACTS)

FACTS [12] is a system composed of static equipment used for the AC transmission of electrical energy. It is meant to enhance controllability and increase power transfer capability of the network. It is generally power electronics based system. FACTS technology opens up new opportunities for controlling power and enhancing the usable capacity of present, new and upgraded lines. FACTS Controllers control the interrelated parameters that govern the operation of transmission systems including series impedance, shunt impedance, current, voltage, phase angle and the damping of oscillations at various frequencies below the rated frequency.

The FACTS technology is not a single high-power controller, but rather a collection of controllers that can be applied individually or in coordination to control one or more interrelated system parameters. Various types of FACTS devices/controllers are listed below:

- Static Var Compensator (SVC)
- Static Synchronous Compensator (STATCOM)
- Static Series Synchronous Compensator (SSSC)
- Unified Power Flow Controller (UPFC)
- Interline Power Flow Controller (IPFC)
- Thyristor Controlled Series Capacitor (TCSC)
- Thyristor Controlled Series Reactor (TCSR)
- Thyristor Controlled Phase Shifting Transformer (TCPST)

3.6 Adopted Control Methodology

In this research work, LFC of multi-area DHPS having two different configurations is carried out by using three different controllers and further their comparative results are also presented. The three different controllers used for LFC are:

3.6.1 Proportional-Integral-Derivative Controller (PID)

A PID controller or three-term controller is a control loop mechanism employing feedback that is widely used in industrial control systems and a variety of other applications requiring continuously modulated control. A PID controller continuously calculates an error value e (t) as the difference between a desired set point (SP) and a measured process variable (PV) and applies a correction based on proportional, integral, and derivative terms (denoted P, I and D respectively), It automatically applies accurate and responsive correction to a control function. PID controller [46,48] has the ability to use the three control terms of proportional, integral and derivative influencing the controller output to apply accurate and optimal control. Figure 3.3 shows the block diagram of PID controller which continuously calculates an error value e(t) as the difference between a desired setpoint SP = r(t) and a measured process variable PV = y(t) and applies a correction based on proportional, integral, and derivative terms. The controller attempts to minimize the error over time by adjustment of a control variable u(t) to a new value determined by a weighted sum of the control terms.

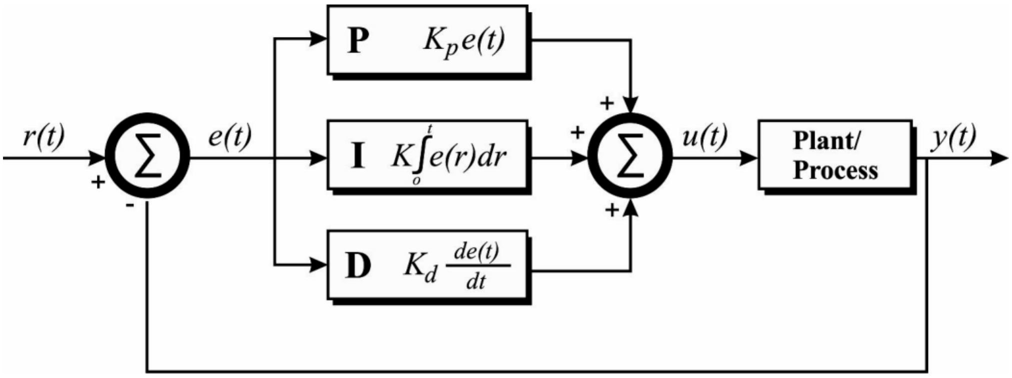


Figure 3.3: Block diagram of PID controller

- Term P is proportional to the current value of the SP − PV error e(t).
- Term I accounts for past values of the SP − PV error and integrate them over time.
- Term D is a best estimate of the future trend of the SP − PV error, based on its current rate of change. It is sometimes called "anticipatory control", as it is effectively seeking to reduce the effect of the SP − PV error by exerting a control influence generated by the rate of error change.

The mathematical equation for the PID controller is given as:

$$u(t) = K_p e(t) + K_i \int_0^t e(t)d(t) + K_d \frac{de(t)}{d(t)} \tag{3.11}$$

u (t) is the output of the controller

K_p is the proportional gain

K_i is the integral gain

K_d is the derivative gain

The various gains of the PID controller are tuned by using MATLAB tuner in this research work.

3.6.2 Fractional-Order PID Controller (FOPID)

Fractional-order calculus is an area of mathematics that deals with derivatives and integrals from non-integer orders. In other words, it is a generalization of the traditional calculus that leads to similar concepts and tools, but with a much wider applicability. FOPID controllers have received a considerable attention in the last years both from academic and industrial point of view. In fact, in principle, they provide more flexibility in the controller design, with respect to the standard PID controllers, because they have five parameters to select (instead of three). Figure 3.4 shows the block diagram of FOPID controller [293-295].

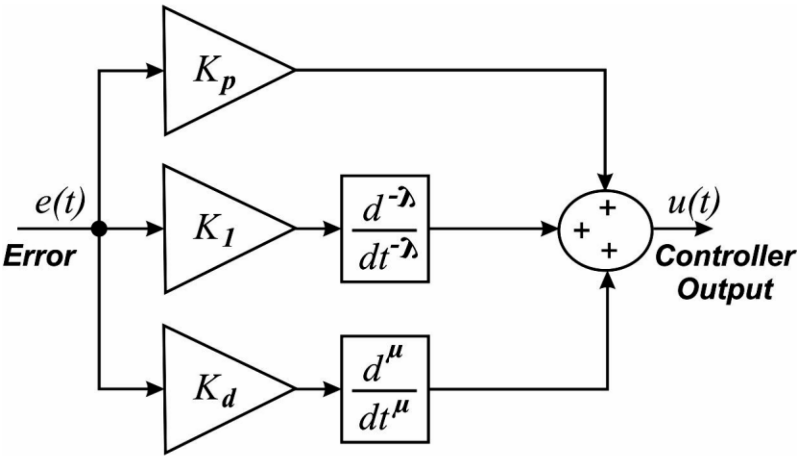


Figure 3.4: Block diagram of FOPID Controller

The FOPID controller time domain representation is given as:

$$u(t) = K_p e(t) + K_i D^{-\lambda} e(t) + K_d D^{\mu} e(t) \tag{3.12}$$

where λ and μ are the non-integer orders of the integral and derivative terms and D is the fractional operator defined by Riemann-Liouville [293]. It is evident that, in FOPID controller, apart from the usual three parameters K_p, K_i, and K_d, the parameters of integral-order λ and derivative-order μ is considered. Hence, the FOPID controller design procedure consists of solving five nonlinear equations with five unknowns K_p, K_i, K_d, λ and μ related to the system. One of the most important advantages of the $PI^{\lambda}D^{\mu}$ controller is the better control of dynamical systems, which is described by fractional order mathematical models. In this research work FOPID controller is implemented using *FOMCON* (Fractional-Order Modeling and Control) toolbox available in MATLAB.

3.6.3 Brain Emotional Learning Based Intelligent Controller (BELBIC)

BELBIC is a non-linear and neuromorphic controller based on the computational learning method to produce control actions which was introduced by Lucas in 2004 [108]. Since BELBIC is a bio-inspired control method used for control and decision making processes, the structure of BELBIC is based on limbic system of the mammalian brain. Control action of BELBIC controller is based on the sensory inputs (SIs) and the emotional cues (ECs). It is a dual feedback system which consumes less processing time. BELBIC technique was applied for SISO, MIMO and nonlinear systems. BELBIC is a direct adaptive, model-free controller with low online computation, simple structure, and fast auto learning. It is very powerful in disturbance handling and robust with respect to parameter variations because of its appropriate learning ability.

The structure of the limbic system is shown in Figure 3.5 [109]. The limbic system supports various functions such as emotion, behavior, motivation, long-term memory and olfaction. The main components of the limbic system that are associated with brain emotion and decision making functions are the amygdala, orbitofrontal cortex (OC), thalamus and the sensory cortex.

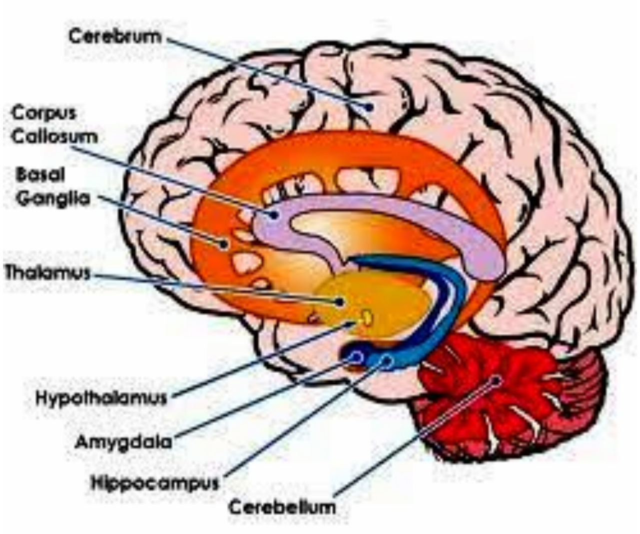


Figure 3.5: The Limbic System

Amygdala is almond shaped which communicates with all the cortices of the limbic system. The amygdale associates between a stimulus and its emotional consequence. In the limbic system, the emotional learning takes place in two steps. First, a particular stimulus is correlated with an emotional response. Second, this emotional consequence shapes an association between the stimulus and the response. The stimulus for instance can be observing a face, detecting a scent or hearing a noise. For these stimuli, the emotional consequence takes place in the amygdala. The amygdala assigns a primary emotional value to each stimulus that has been paired with reinforcement that is the reward of punishment that the mammal receives. This function of the amygdala is aided by the OC which is involved in the detection of omission of reinforcement. Amygdala acts as an actuator and OC acts as a preventer. The computational model of emotional learning based on Moren and Balkenius model [109] is shown in Figure 3.6.

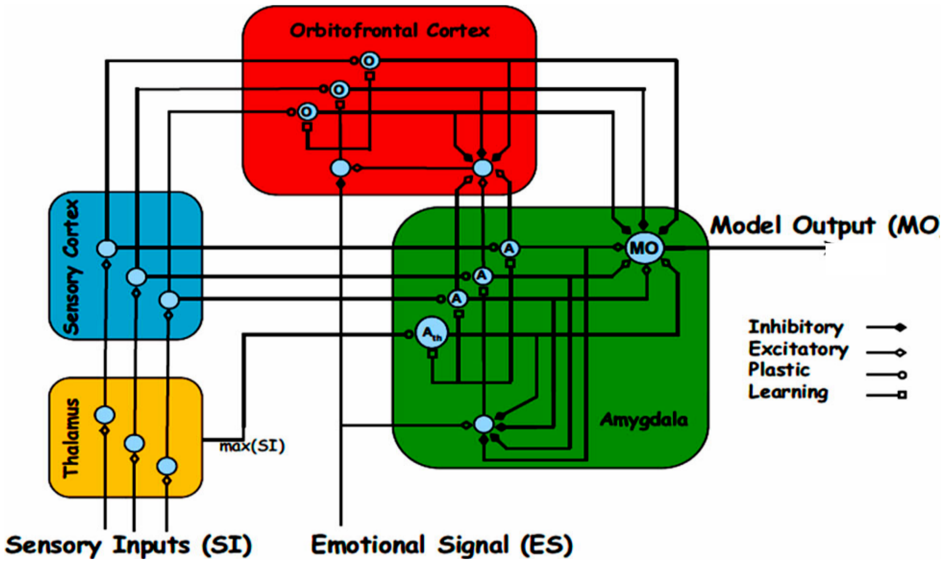


Figure 3.6: Computational model of emotional learning

Thalamus and cortical areas send inputs to Amygdala while Amygdala and cortical areas (OC and Sensory Cortex) sends inputs to Orbitofrontal. A reinforcing signal (Emotional signal/Primary Reward) is also received by the system along with Sensory Cortex inputs. One of the tasks is to determine the SIs. BELBIC controller has two states for each SI. One of these two states is Amygdala's output and another is the output of OC. The number of SIs plays a key role in BELBIC controller.

The output of the BELBIC model is given as:

$$MO = \sum_i A_i - \sum_i OC_i \tag{3.13}$$

where A_i and OC_i are the Amygdala and Orbitofrontal Cortex outputs, respectively. i corresponds to number of sensory inputs. (i = 1, 2, 3 . . .).

The Amygdala and OC outputs are calculated as:

$$A_i = V_i SI_i \tag{3.14}$$

$$OC_i = W_i SI_i \tag{3.15}$$

V, W are two states for the associated sensory input.

These two are updated by the following equations:

$$\Delta V_i = \alpha SI_i \max\left(0, ES - \sum_i A_i\right) \tag{3.16}$$

$$\Delta W_i = \beta SI_i \left(MO - ES\right) \tag{3.17}$$

where α and β correspond to training coefficients in these equations. In BELBIC controller, there is a function named Reward (Emotional signal). This function has a great role in BELBIC controller. The controller strives to boost this reward. The designer must define a reward function having its maximum values in the desired regions. Equation (3.13) represents the control effort of BELBIC controller. The amygdala does not have the capability to forget any emotional response that it ever learned. The function of the OC is to respond to any inappropriate response.

Figure 3.7 represents the schematic model of BELBIC based control system.

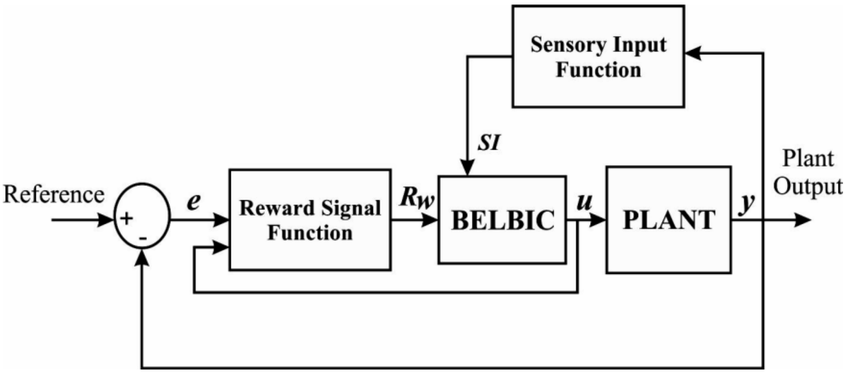


Figure 3.7: Control system configuration using BELBIC

Figure 3.7 depicts that the BELBIC controller has two feedback loops viz.., the plant output feedback loop and the BELBIC output feedback loop. In this way the BELBIC acts as a dual feedback system. These inputs to the controller form the SIs and ECs, based on which the amygdala and the OC of the controller produce the necessary output (u).

For damping of frequency and inter area tie-line power deviations, BELBIC controller is considered in each control area. According to Figure 3.7, the LFC system uses ACE as the input signal to the BELBIC controller. The plant input, output, and reference account for SI and reward signal (emotional signal). It mainly depends on the designer to find a suitable control action. There are various tuning parameters for each SI, the general procedure for tuning these parameters is trial and error [108].

ECs and SI block functions considered in this work are:

$$EC = k_1(ACE_i) + k_2 \frac{d(ACE_i)}{dt} + k_3 \int (ACE_i).dt \tag{3.18}$$

$$SI = k_4 |ACE_i| + k_5 |ACE_i.\Delta f_i| \tag{3.19}$$

where ACE_i and Δf_i are the area control error and frequency deviation for the ith area, respectively. k_1, k_2, k_3, k_4, and k_5 are the gains to be tuned properly for the satisfactory operation of the controller. BELBIC toolbox available in the Simulink library is used for designing BELBIC controller. Gains k_1 and k_2 tune the overshoot, gain k_3 takes care of the settling time, the gain k_4 is responsible for tuning the steady-state error and finally, the gain k_5 accounts for smoothing the beginning of the response [108].

3.7 Different Power System Configurations

Present work focuses on the LFC of DHPS comprising of conventional and non-conventional energy sources system using PID, FOPID and BELBIC controller. Two different DHPS configurations are considered in this research work.

3.7.1 Three-area Deregulated Hybrid Power System (DHPS)

Configuration-1 comprises of a three-area DHPS. Area-1 comprises of a thermal, hydro and solar-battery unit. A SC is also integrated to this area. Area-2 consists of thermal, hydro and fuel cell–aqua electrolyser unit. In Area-3 biomass based HDGT, DEG contributes to power generation along with thermal and hydro. TCPS is placed in series with all the tie-lines. The PID controller is adopted here for the LFC scheme. Figure 3.8 represents the transfer function model of three-area DHPS.

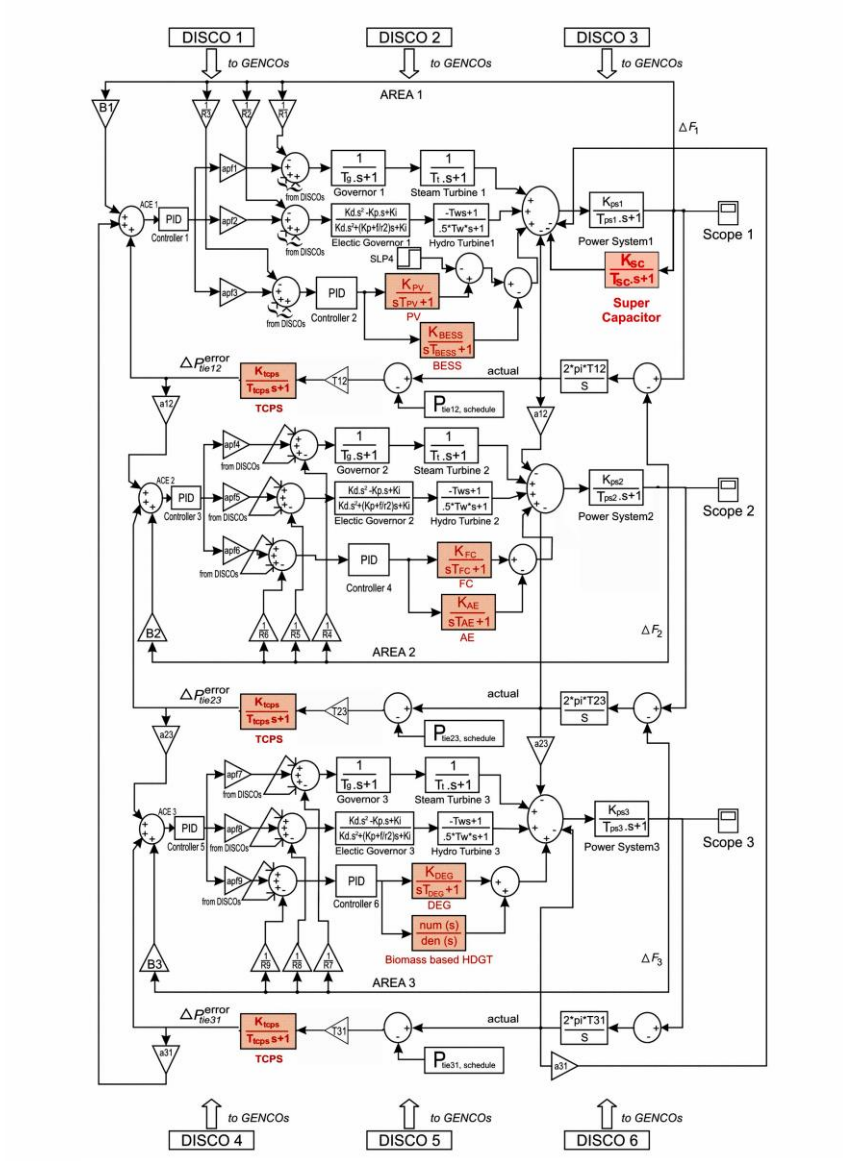


Figure 3.8: Transfer function model of three-area DHPS

Various generation and storage modules used in the above shown three-area DHPS are discussed below along with TCPS and SC.

3.7.1.1 Thermal unit

A simple thermal unit without reheating and GRC is presented in the proposed LFC scheme. LFC model of thermal unit mainly consists of three parts; Turbine speed governing system model, Turbine model and Generator load model. All these models are discussed below.

3.7.1.1.1 Speed Governor Model

The schematic diagram of turbine speed governing system of thermal power generation is shown in Figure 3.9 [44]. The turbine speed governing system consists of the speed governor, hydraulic amplifier, linkage mechanism and speed changer. The change in speed causes inward or outward motion of fly-ball which in turn causes the upward or downward movement of point B in linkage mechanism. Thus it senses the change in speed or frequency. The hydraulic amplifier consists of a pilot valve and main piston. To control the turbine input it is necessary to control the steam valve opening which can be done by converting the low power motion of pilot valve to high power motion of level piston valve. Linkage mechanism controls the valve movements. The setting of steady state output power of the turbine is provided by the speed changer.

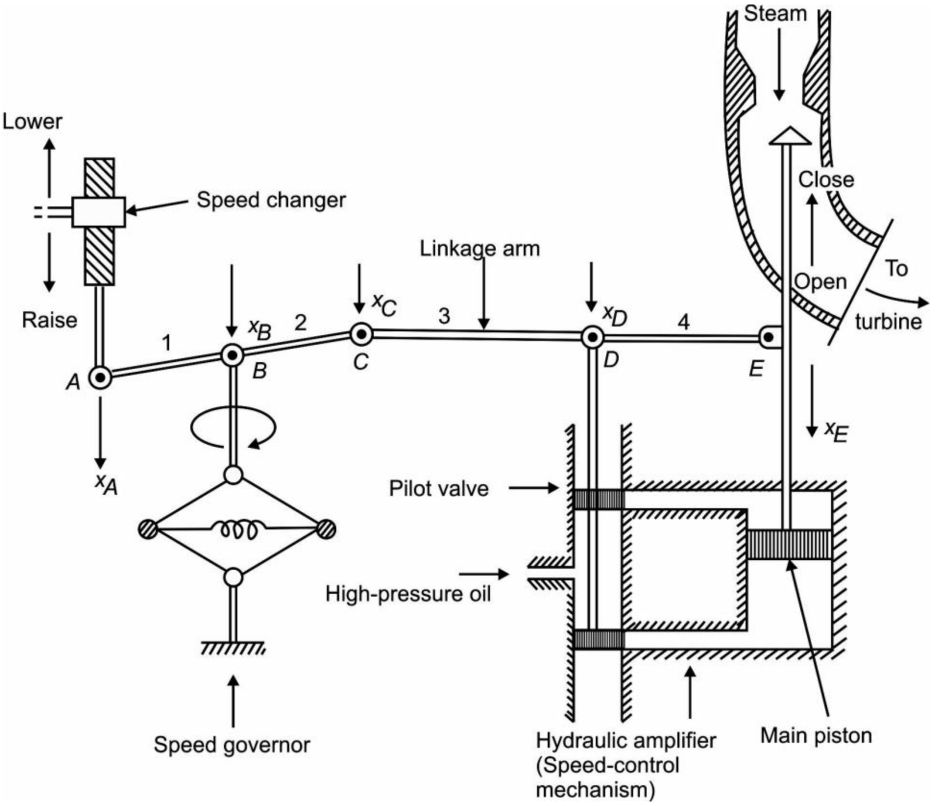


Figure 3.9: Turbine speed governing system

Under steady state condition, linkage mechanism of turbine speed governing system is stationary, the pilot valve is closed and the steam valve is opened by a definite magnitude as per the steady state power output. At this condition turbine runs at constant speed. The transfer function of speed governor is represented by the equation (3.20) [2]:

$$G = \frac{K_g}{sT_g + 1} \tag{3.20}$$

3.7.1.1.2 Turbine Model

It is necessary to relate the change in power output of the steam turbine to the change in its steam valve opening. The transfer function model of non reheat type turbine is represented by equation 3.21 [2]:

$$G = \frac{K_t}{sT_t + 1} \tag{3.21}$$

3.7.1.1.3 Generator Load Model

Generator load model describes the relation between change in frequency and change in power generation subject to the change in load demand. There is a change in the generation by an amount of ΔP_G, if ΔP_D is the change in load demand. Hence, the increment in power input to the generator–load system is ΔP_G - ΔP_D. The transfer function for generator load model is represented by equation (3.22) [2]:

$$G = \frac{K_{ps}}{sT_{ps} + 1} \tag{3.22}$$

3.7.1.2 Hydro Unit

Like thermal generating unit LFC model of hydro generating unit has also three major parts: hydro governing system model, hydro turbine model and generator load model. These models are described below.

3.7.1.2.1 Hydro Governor Model

The primary task of the hydro governing system is to regulate the water flow through the penstock to maintain a constant turbine speed. Modern speed governors for hydraulic turbines use electro hydraulic systems. Functionally, their operation is very similar to that of mechanical hydraulic governors. Speed sensing, permanent droop, temporary droop, and other measuring and computing functions are performed electrically. The transfer function of electro hydraulic governor (PID governor) is represented by equation (3.23) [2]:

$$G = \frac{Kd.s^2 + Kp.s + Ki}{Kd.s^2 + (Kp + f/R)s + Ki} \tag{3.23}$$

3.7.1.2.2 Hydro Turbine Model

In this section model of Francis turbine is discussed. If pressure across the turbine fall then the output decreases. The steady state performance of turbine is obtained for constant flow rate of water through the penstock. The following assumptions are adopted to formulate the same.

- The frictional resistance of the turbine blade is not considered in this case.
- The water hammer on the penstock is assumed to be neglected.
- The incompressible fluid is considered.
- The velocity of the water in penstock varies proportionately with the gate opening.
- The output from the turbine is directly proportional to the product of velocity of water flow and the water head.

The transfer function model of hydro turbine is represented by equation (3.24) [2]:

$$G = \frac{1 - T_w s}{1 + 0.5T_w s} \tag{3.24}$$

3.7.1.3 Solar-Battery Unit

In the proposed scheme solar PV is made to participate in LFC. Solar unit is supposed to deliver fraction of incremental power as demanded in the multi-area interconnected power system according the contracted DPM. This is feasible only if solar irradiation increases enough to make the PV system deliver the incremental power. But in practice as solar irradiation is uncontrollable. Hence, concept of ESS is incorporated. The ESS supplies the incremental load assigned to PV system if PV fails to do so. But when the solar irradiation is higher than its reference value, it can produce equal or more than its share of load and incremental load. The extra energy is utilized to charge battery. If there is still surplus power after supplying the load and the battery charge, that power is treated as input signal to the power system block [4,6].

In this work, a 5MW solar photovoltaic unit is used. In the absence of solar irradiation battery unit supplies both load and incremental load assigned to solar unit. When both the solar and battery unit are absent then the load assigned to the solar-battery unit is considered as an uncontracted load from that area. In that situation, the area participation factor (apf) of other generating units which are present in that area changes. A 5MW, 10MWh battery bank [296] is considered in this study. The simplified transfer function used for solar power generation and battery energy storage is given by equation (3.25,3.26) [238,4] respectively.

$$G_{PV} = \frac{K_{PV}}{1+sT_{PV}} \tag{3.25}$$

$$G_{BESS} = \frac{K_{BESS}}{1+sT_{BESS}} \tag{3.26}$$

3.7.1.4 Fuel Cell–Aqua Electrolyser Unit

FC is another promising RES chosen in the said hybrid power generation system. Unlike wind and solar, FC is a controllable source of energy. A part of energy produced by FC is consumed by AE unit for producing hydrogen which is used as fuel in FC. In this work, a 180kW FC is used. The simplified transfer functions used for FC and aqua electrolyzer are represented by equations (3.27,3.28) [4] respectively.

$$G_{FC} = \frac{K_{FC}}{1+sT_{FC}} \tag{3.27}$$

$$G_{AE} = \frac{K_{AE}}{1+sT_{AE}} \tag{3.28}$$

3.7.1.5 Diesel Engine Generator (DEG)

The DEG is in action autonomously to supply the deficit power in the hybrid DG system to meet the supply-load demand balance condition. A diesel generator is a nonlinear system because of the presence of a nonlinear, time-varying dead time between the injection and production of mechanical torque. In this work, a 20kW DEG set is used. The transfer function of DEG is represented by equation (3.29) [4].

$$G_{DEG} = \frac{K_{DEG}}{1+sT_{DEG}} \tag{3.29}$$

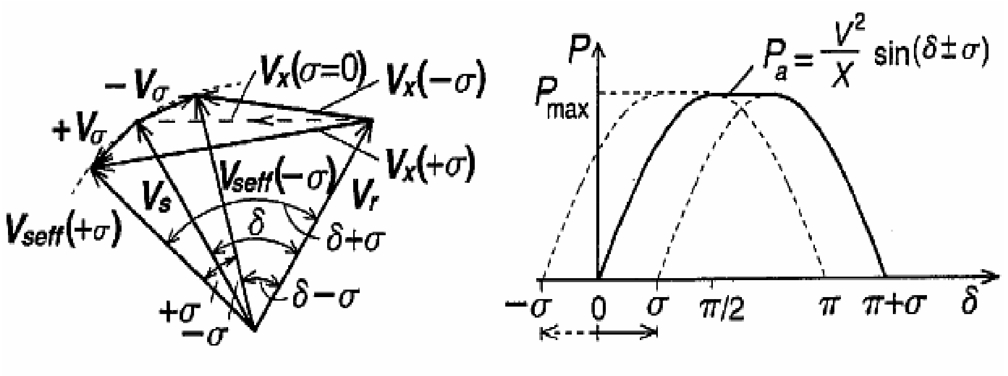
3.7.1.6 Biomass based Heavy Duty Gas Turbine (HDGT)

Biomass is a renewable and sustainable source of energy used to produce electricity. It is a fuel developed from organic matter. When things like garbage, human and animal waste, dead animals rot, they release a gas called biogas (also known as methane gas or landfill gas). This gas is used to rotate turbines as the gas turbines are one of the main sources for power generation. After conditioning biogas fuels can be used in gas turbines to produce power. HDGT are widely used to generate electric power. In this work, a 18.5MW biomass based HDGT plant is considered. Linearized transfer function model of HDGT plant is represented by equation (3.30) [214].

$$G(s)=\frac{-0.06551s^3-2.784s^2-31.52s+2010.01}{s^4+42.54s^3+501.7s^2+1020s+2092} \tag{3.30}$$

3.7.1.7 Thyristor Controlled Phase Shifter (TCPS)

TCPS is an effective apparatus for the tie-line power flow control of interconnected power system. It does so by changing the relative phase angle between the system voltages. TCPS is considered as a sinusoidal ac voltage source with controllable amplitude and phase angle. Thus the effective sending end voltage becomes sum of the prevailing sending end voltage and the voltage provided by the TCPS. For an ideal phase angle regulator the angle of phasor V_σ relative to phasor V_S is stipulated to vary with σ , as shown in Figure 3.10 [12].



(a) **(b)**

Figure 3.10: (a) Corresponding phasor diagram (b) Transmitted power vs angle characteristics

The relationship between real power *P* and angles *δ, σ* is shown plotted in Figure 3.10 (b). It is observed that although the phase angle regulator doesn’t increase the transmittable power of the uncompensated line, it makes it theoretically possible to keep the power at its maximum value at any angle *δ* in the range $\pi/2<\delta<\pi/2+o$ by, in effect shifting the P vs δ curve to the right. Schematic of a two-area interconnected power system with TCPS in series with the tie-line is shown in Figure 3.11.

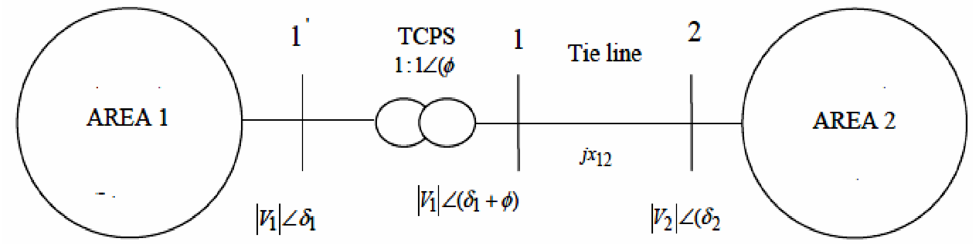


Figure 3.11: Schematic of a two-area interconnected power system with TCPS in series with the tie-line

The interconnected tie-line power flow from area 1 to area 2 without considering TCPS is represented by the following equation [131]:

$$\Lambda P^{0}{}_{tie12} = \frac{2\pi T^{0}{}_{12}}{s}(\Delta f_1 - \Delta f_2) \tag{3.31}$$

where, $T^0{}_{12}$ is the synchronizing coefficient and Δf_1, Δf_2 are the frequency deviations of area 1 and area 2 respectively. With the TCPS placed in series with the tie-line near area 1 as shown in Figure 3.11, the current flowing from area1 to area2 is represented by the following equation [131]:

$$i_{12} = \frac{|V_1|\angle(\delta_1 + \phi) - |V_2|\angle\delta_2}{jX_{12}} \tag{3.32}$$

And the complex power is represented as:

$$P_{tie12} - jQ_{tie12} = |V_1|\angle-(\delta_1 + \phi)[\frac{|V_1|\angle(\delta_1 + \phi) - |V_2|\angle\delta_2}{jX_{12}}] \tag{3.33}$$

Using equations (3.32,3.33) and separating the real and imaginary parts

$$P_{tie12} = \frac{|V_1||V_2|}{X_{12}}\sin(\delta_1 - \delta_2 + \phi) \tag{3.34}$$

Perturbing δ_1, δ_2 and ϕ from their nominal values δ_1^0, δ_2^0 and ϕ^0 respectively, we get

$$\Delta P_{tie12} = \frac{|V_1||V_2|}{X_{12}}\cos(\delta_1^{0} - \delta_2^{0} + \phi^{0})\sin(\delta_1 - \delta_2 + \phi) \tag{3.35}$$

The small change in real power load causes smaller variation in bus voltage angles and TCPS phase angle. Thus, in effect ($\Delta\delta_1$ - $\Delta\delta_2$ +$\Delta\ \phi$) is very small and hence

$$\sin(\Delta\delta_1 - \Delta\delta_2 + \Delta\phi) \cong (\Delta\delta_1 - \Delta\delta_2 + \Delta\phi) \tag{3.36}$$

$$\therefore \Delta P_{tie12} = \frac{|V_1||V_2|}{X_{12}}\cos(\delta_1^{0} - \delta_2^{0} + \phi^{0})(\Delta\delta_1 - \Delta\delta_2 + \Delta\phi) \tag{3.37}$$

Let

$$T_{12} = \frac{|V_1||V_2|}{X_{12}}\cos(\delta_1^{0} - \delta_2^{0} + \phi^{0}) \tag{3.38}$$

Thus, equation (3.37) reduces to

$$\Delta P_{tie12} = T_{12}(\Delta\delta_1 - \Delta\delta_2 + \Delta\phi) \tag{3.39}$$

$$\therefore P_{tie12} = T_{12}(\Delta\delta_1 - \Delta\delta_2) + T_{12}\Delta\phi \tag{3.40}$$

It is known that $\Delta\delta_1 = 2\pi\int \Delta f_1 \mathrm{dt}$ and $\Delta\delta_2 = 2\pi\int \Delta f_2 \mathrm{dt}$ (3.41)

From Equation (3.40) and (3.41)

$$\Delta P_{tie12} = 2\pi T_{12}(\int \Delta f_1 dt - \int \Delta f_2 dt) + T_{12}\Delta\phi \tag{3.42}$$

Laplace transform of equation (3.42) yields

$$\Delta P_{tie12}(s) = \frac{2\pi T_{12}}{s}[\Delta F_1(s) - \Delta F_2(s)] + T_{12}\Delta\phi(s) \tag{3.43}$$

It is evident from equation (3.42) the tie-line power can be controlled by controlling $\Delta\phi$, i.e. the phase shifter angle. The phase shifter angle $\Delta\phi$ (s) is represented as:

$$\Delta\phi(s) = \frac{K_\phi}{1 + sT_{PS}}\Delta Error_1(s) \tag{3.44}$$

$\Delta Error_1(s)$ is the control signal which controls the phase angle of the phase shifter. Thus equation (3.43) can be written as

$$\Delta P_{tie12}(s) = \frac{2\pi T_{12}}{s}[\Delta F_1(s) - \Delta F_2(s)] + T_{12}\frac{K_\phi}{1 + sT_{PS}}\Delta Error_1(s) \tag{3.45}$$

3.7.1.8 Supercapacitor (SC)

SC is an electrochemical device that consists of two porous electrodes separated by an ion- exchange membrane and a potassium hydroxide electrolyte. It is also known as Electric Double Layer Capacitor (EDLC) [197]. In SCs the formation of a double layer of very small thickness results in a high value of specific capacitance. SCs have 100–1000 times the capacitance per unit volume compared to the conventional electrolytic capacitor. Compact in size, SCs can store higher amount of energy than conventional capacitors. SCs possess high power density and energy density. They can be charged/discharged quickly as compared to batteries and conventional capacitors. They can be cycled millions of times and possess longer lifetime. SC is a fast acting storage system that enhances the system dynamics [168,198].

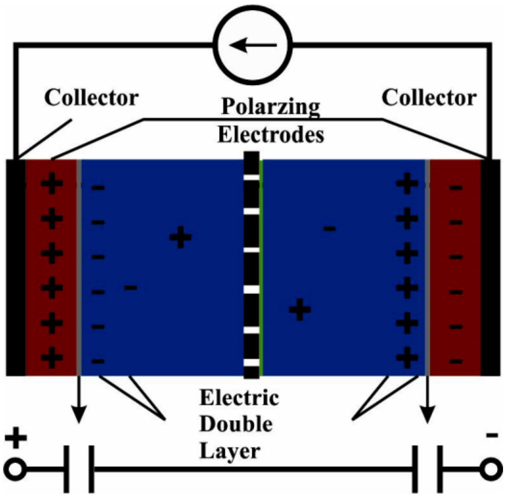


Figure 3.12: Electric Double Layer Capacitor

The transfer function of the SC is represented by equation (3.46) [197]

$$G_{SC} = \frac{K_{SC}}{1 + sT_{SC}} \tag{3.46}$$

3.7.2 Two-area Deregulated Hybrid Power System

Configuration-2 comprises of a two-area DHPS. Area-1 consists of a thermal, hydro and solar PV. Random variation of 2% in solar power is considered. EVs are used to handle intermittency of solar power. EVs together with RESs provide sustainable mobility in the electrical power system. Area-2 comprises of thermal, hydro and a biomass based HDGT. To make it more realistic, effect of nonlinearity constraints GRC, GDB and time delay in communication channel is also considered. The performance of the developed DHPS model is investigated by using different controllers. Comparative results of various controllers in terms of settling time and peak over/undershoot are presented. Sensitivity analysis is carried out to check the robustness of controllers.

Figure 3.13 represents the transfer function model of two area hybrid deregulated power system.

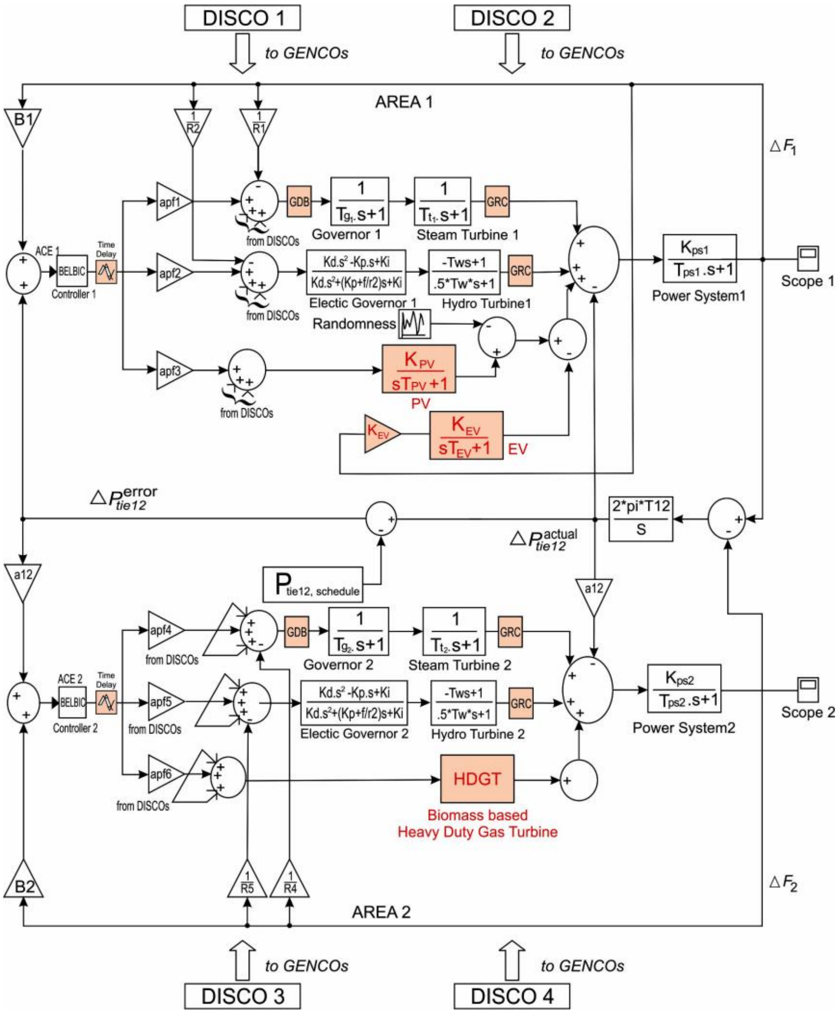


Figure 3.13: Transfer function model of two-area DHPS

Various generation modules of configuration-2 of electrical power system are already discussed under configuration-1. But modeling of EVs (Distributed Energy Storage System) incorporated in area-1 to handle intermittency of solar power is discussed in the next section.

3.7.2.1 Electric Vehicle

Intermittency associated with RESs result in an increase in frequency deviations. When idle, EVs provide a frequency regulation strategy connected to the electric grid [8]. An aggregate model of EV fleets comprising of battery charger, primary frequency control and LFC is shown below:

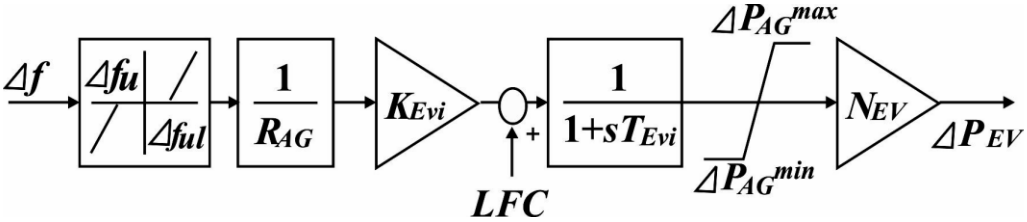


Figure 3.14: EVs aggregate model structure

Dead band function with droop characteristics is provided with each EV as EVs might get disconnected from the grid resulting in undesired frequency response. Dead band upper limit (Δf_{UL}) and lower limit value (Δf_{LL}) is considered as 10 and −10mHz, respectively. The value of aggregate model droop coefficient (R_{AG}) is the same as conventional units, i.e. 2.4Hz/p.u.MW. In Figure 3.14, K_{EVi} and T_{EVi} corresponds to EV gain and battery time constant, respectively. State of charge (SOC) of EV determines the value of K_{EVi}. ΔP_{EVi} is the incremental generation change of EV (p.u.). ΔP_{AG}^{max} and ΔP_{AG}^{min} denotes the maximum and minimum power output of EV fleets and is calculated as:

$$\Delta P_{AG}{}^{\max} = +[\frac{1}{N_{EV}} \times (\Delta P_{EVi})] \tag{3.47}$$

$$\Delta P_{AG}{}^{\min} = -[\frac{1}{N_{EVi}} \times (\Delta P_{EVi})] \tag{3.48}$$

where N_{EV} represents number of electric vehicles connected. For analysis, the charging and discharging capacity of EV is considered within ±6 kW.

The value of K_{EVi} varies with SOC level of the battery (li-ion) which represents the participation of EVs in LFC when connected to grid. Figure 3.15 shows the value of K_{EVi} with respect to SOC.

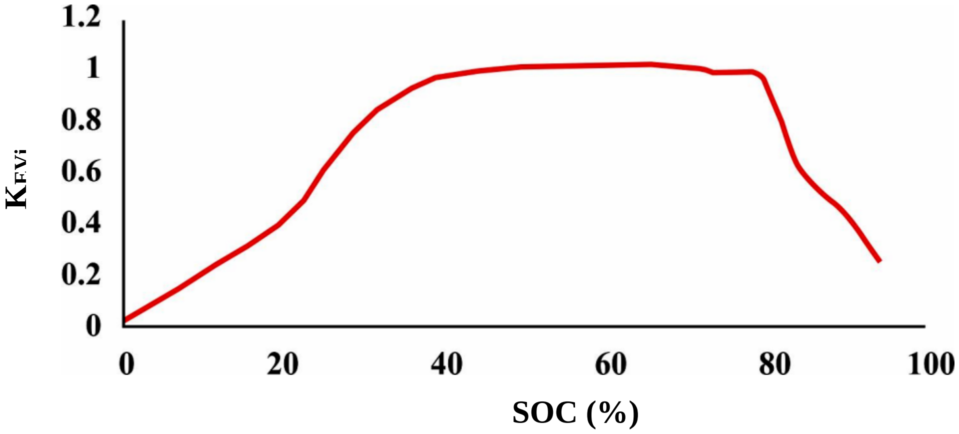


Figure 3.15: K_{EVi} vs State of charge

CHAPTER 4
RESULTS AND DISCUSSION

In the present work, two DHPS models have been developed and the proposed optimal LFC scheme is implemented on these developed power system models. This first DHPS model consists of three-areas while the second consists of two-areas. Various DG sources are integrated with the conventional energy sources in these power system models.

4.1 Frequency and Tie–Line Power Dynamics of Three-Area DHPS due to Sudden Load Increment

In this case LFC scheme is implemented on three-area DHPS configuration. Impact of TCPS-SC unit in improving LFC performance is analyzed here.

4.1.1 System Responses without TCPS-SC unit

LFC scheme is implemented on a three-area DHPS without integrating TCPS-SC unit. Bilateral contract scenario has been considered wherein all the areas have unequal shares in the generation process as defined by the following DPM:

$$\mathrm{DPM} = \begin{pmatrix} 0.2 & 0.2 & 0.137 & 0.137 & 0.277 & 0.277 \\ 0.2 & 0.2 & 0.137 & 0.137 & 0.137 & 0.137 \\ 0.0135 & 0.0135 & 0.0135 & 0.0135 & 0.0135 & 0.0135 \\ 0.137 & 0.137 & 0.2 & 0.2 & 0.137 & 0.137 \\ 0.137 & 0.137 & 0.2 & 0.2 & 0.137 & 0.137 \\ 0.0185 & 0.0185 & 0.0185 & 0.0185 & 0.0185 & 0.0185 \\ 0.137 & 0.137 & 0.137 & 0.137 & 0.13 & 0.13 \\ 0.137 & 0.137 & 0.137 & 0.137 & 0.13 & 0.13 \\ 0.02 & 0.02 & 0.02 & 0.02 & 0.02 & 0.02 \end{pmatrix} \quad (4.1)$$

Each Disco demands 0.1 pu MW total power from GENCOs as defined by entries in DPM and each GENCO participate in AGC as defined by following apf's:

$apf_1 = 0.5$, $apf_2 = 0.3$, $apf_3 = 0.2$, $apf_4 = 0.5$, $apf_5 = 0.3$, $apf_6 = 0.2$

$apf_7 = 0.5$, $apf_8 = 0.3$, $apf_9 = 0.2$

$GENCO_1$ (scheduled)

$\Delta P_{g1} = (0.2+0.2+0.137+0.137+0.277+0.277)*0.1$

$= 0.1228$pu MW

Similarly,

$\Delta Pg_2 = 0.0948$pu MW

$\Delta Pg_3 = 0.0081$pu MW

$\Delta Pg_4 = 0.0948$pu MW

$\Delta Pg_5 = 0.0948$pu MW

$\Delta Pg_6 = 0.0111$pu MW

$\Delta Pg_7 = 0.0808$pu MW

$\Delta Pg_8 = 0.0808$pu MW

$\Delta Pg_9 = 0.0120$pu MW

Scheduled tie-line power flow from area-1 to area-2

$\Delta P_{tie12,sch}$ = Demand of DISCOs in area-2 from GENCOs in area-1 – Demand of DISCOs in area-1from GENCOs in area-2

$= (cpf_{13} + cpf_{23} + cpf_{33})\ \Delta P_{L3} + (cpf_{14} + cpf_{24} + cpf_{34})\ \Delta P_{L4} – (cpf_{41} + cpf_{51} + cpf_{61})\ \Delta P_{L1} + (cpf_{42} + cpf_{52} + cpf_{62})\ \Delta P_{L2}$

$= (0.137 + 0.137 + 0.0135)*0.1 + (0.137 + 0.137 + 0.0135)*0.1 - (0.137 + 0.137 + 0.0185)*0.1 + (0.137 + 0.137 + 0.0185)*0.1$

$= 0.0575 – 0.0585$

$= -0.001$pu MW

Similarly,

$\Delta Ptie_{23,sch} = -0.0003$pu MW

$\Delta P_{tie31,sch} = -0.0267$pu MW

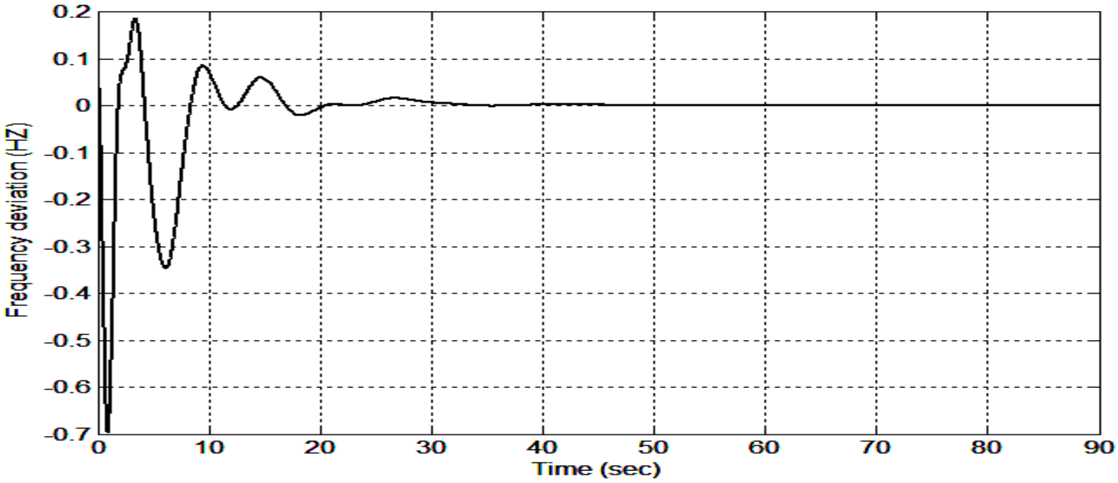


Figure 4.1: Dynamic frequency response of area-1 without TCPS-SC unit

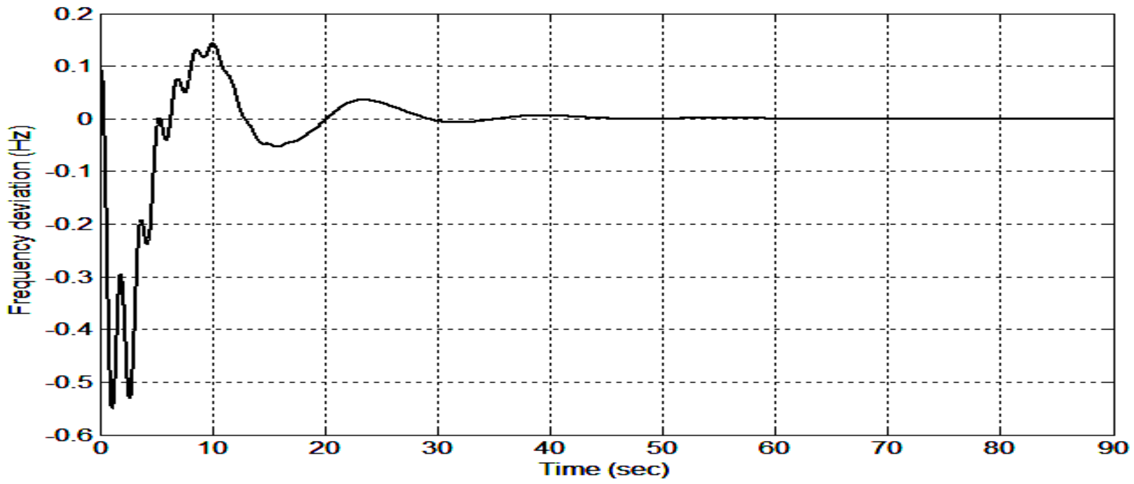


Figure 4.2: Dynamic frequency response of area-2 without TCPS-SC unit

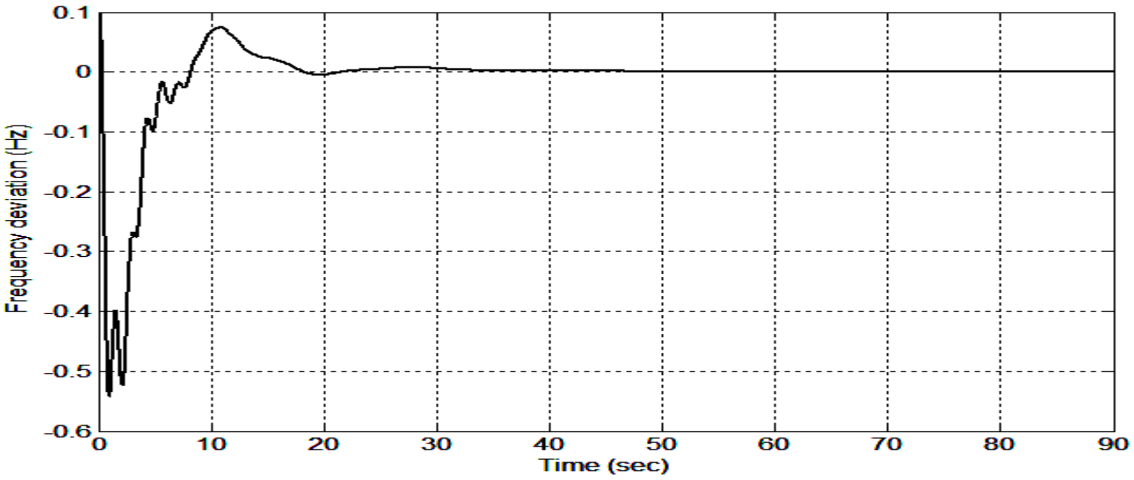


Figure 4.3: Dynamic frequency response of area-3 without TCPS-SC unit

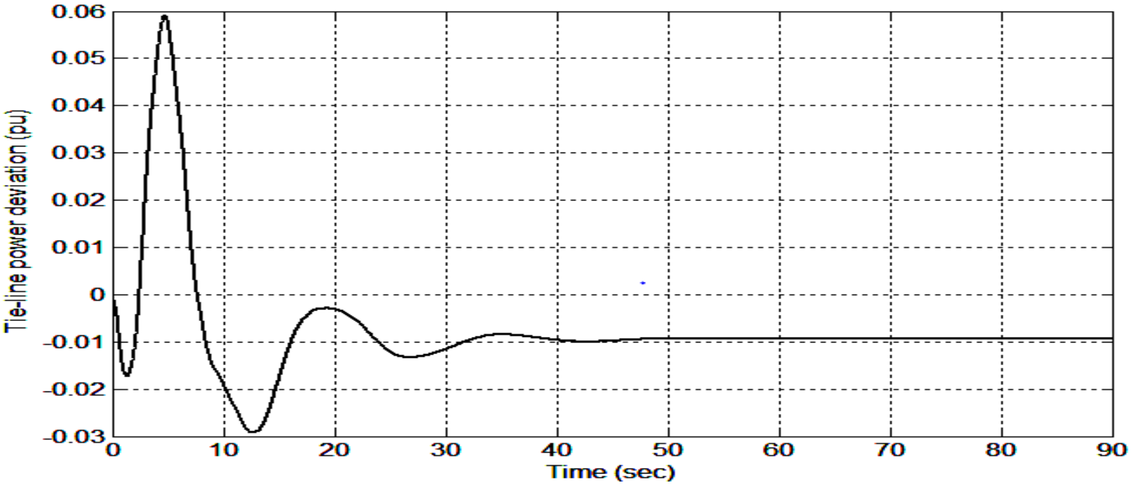


Figure 4.4: Dynamic tie-line$_{12}$ power response without TCPS-SC unit

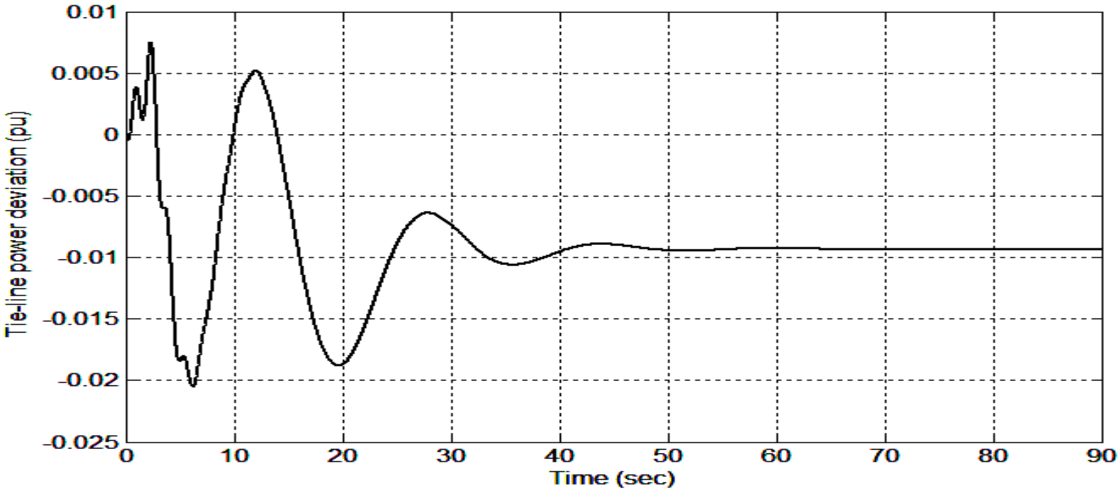


Figure 4.5: Dynamic tie-line$_{23}$ power response without TCPS-SC unit

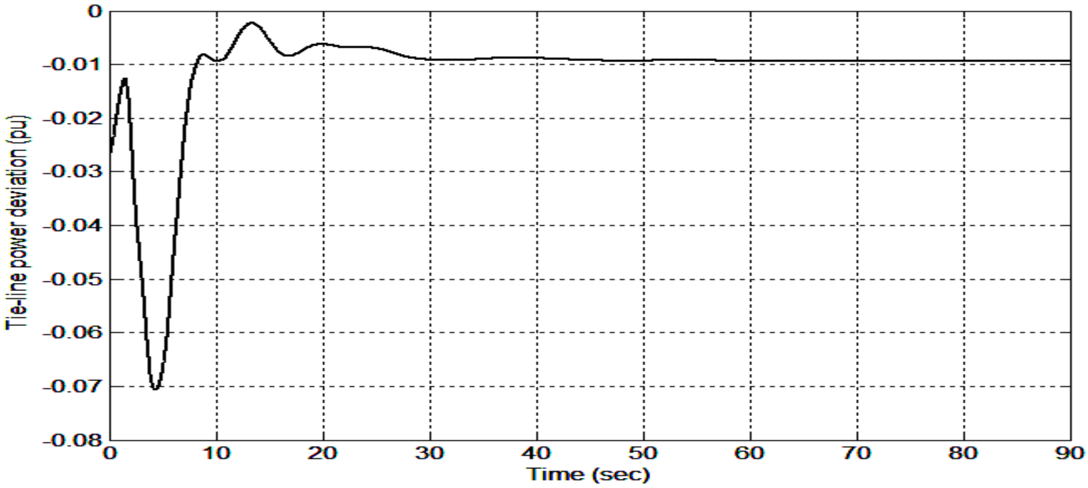


Figure 4.6: Dynamic tie-line$_{31}$ power response without TCPS-SC unit

TABLE 4.1: Frequency response characteristicswithout TCPS-SC unit

	Settling time (sec)			**Peak over/undershoot (pu)**		
	Area1 Δf_1	**Area2** Δf_2	**Area3** Δf_3	**Area1** Δf_1	**Area 2** Δf_2	**Area3** Δf_3
Without TCPS-SC unit	34	44	35	-0.697	-0.555	-0.543

TABLE 4.2: Tie-line power response characteristics without TCPS-SC unit

	Settling time (sec)			**Peak over/undershoot (pu)**		
	ΔP_{12}	ΔP_{23}	ΔP_{31}	ΔP_{12}	ΔP_{23}	ΔP_{31}
Without TCPS-SC unit	50	60	40	.0.059	-0.021	-0.071

Figures 4.1-4.6 represents the dynamic frequency and tie-line power response of three-area DHPS without TCPS-SC unit. Frequency restoration characteristics are shown in Figures 4.1-4.3. The frequency deviation diminishes to zero in near about 34 seconds in area-1, 44 seconds and 35 seconds in area-2 and area-3 respectively. As, each DISCO demands 0.1p.u more than the normal load demand, frequency of the interconnected power system begins to fluctuate. This situation arises due to unbalance of power demand and power generation. To restore frequency to its normal value, LFC comes into action. Power generation of each GENCO increases to match the load demand and generation according to the contract. The tie-line power dynamics are shown in Figures 4.4-4.6. Due to incremental load change of each DISCO, every GENCO participates in it. Every DISCO takes power from each GENCO in its own area and from other areas according to the cpf's. Hence, power flows from one area to other through tie-line. The study of tie-line power flow reveals that tie-line$_{12}$ carries power of 0.001pu from area 2 to area 1 while tie-line$_{23}$ carries power of 0.0003pu from area 3 to area 2. Tie-line$_{31}$ carries power of 0.0267pu from area 1 to area 3. Frequency deviations and tie-line power deviations are evaluated in terms of settling time, over/undershoot which are depicted in Tables 4.1 and 4.2.

Table 4.3: Gains of PID controller without TCPS-SC unit

Controller	**K_p**	**Ki**	**K_d**
PID 1	0.51	-1.00	0.02
PID 2	6.94	-0.61	-9.27
PID 3	0.35	-0.30	0.15
PID 4	8.87	6.23	7.73
PID 5	0.35	-0.21	0.04
PID 6	7.75	1.11	-15.82

4.1.2 System Responses with TCPS-SC unit

LFC scheme is implemented for a three-area deregulated hybrid power system integrated with TCPS-SC unit. The simulated results are shown below.

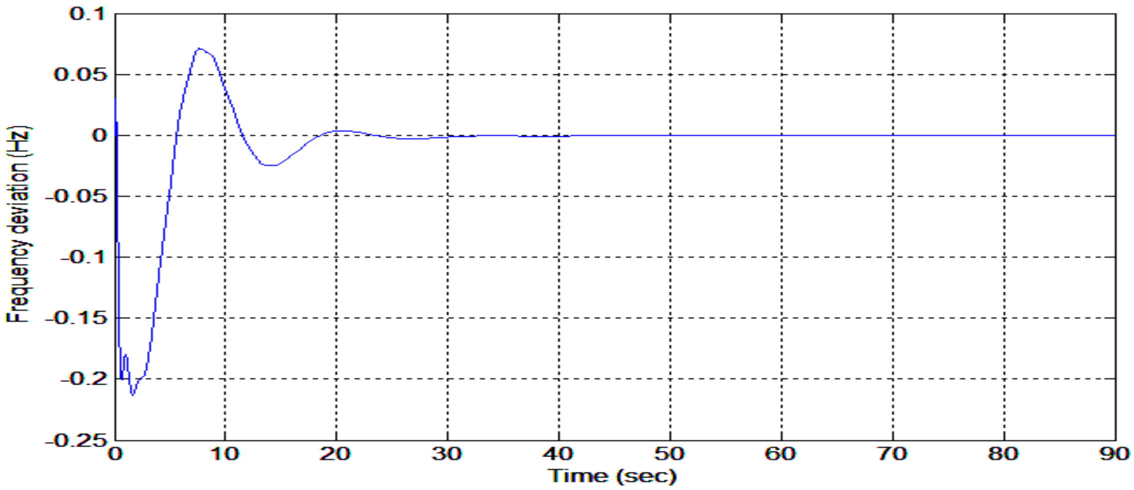


Figure 4.7: Dynamic frequency response of area-1 integrated with TCPS-SC unit

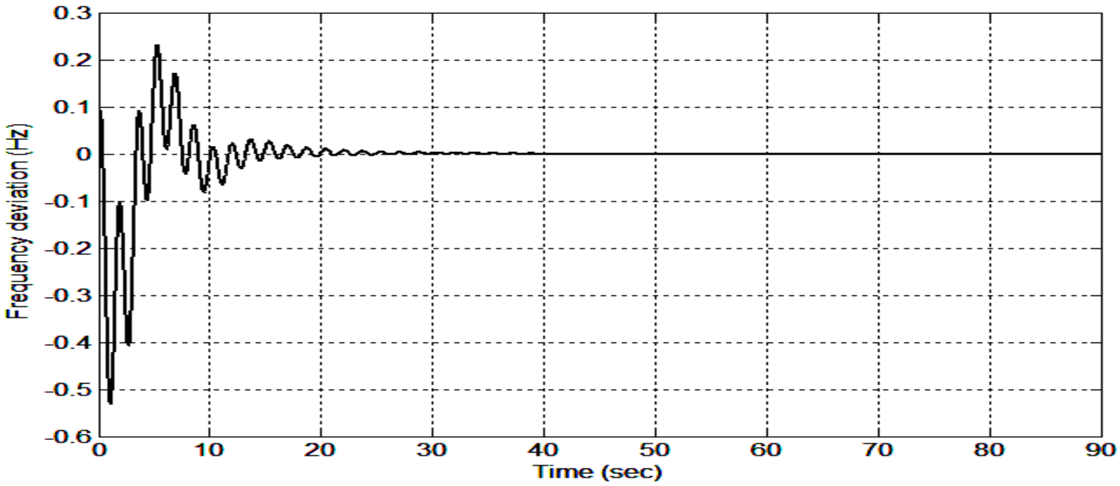


Figure 4.8: Dynamic frequency response of area-2 integrated with TCPS-SC unit

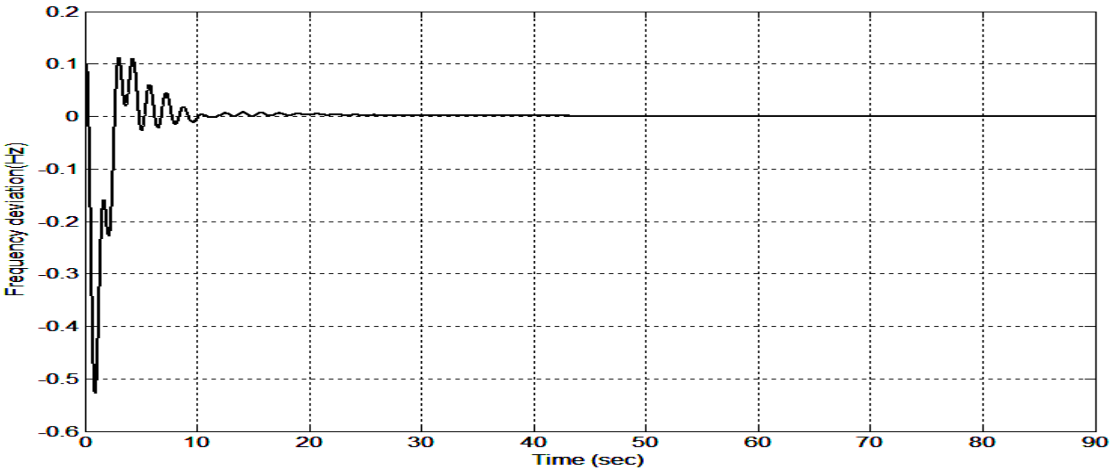


Figure 4.9: Dynamic frequency response of area-3 integrated with TCPS-SC unit

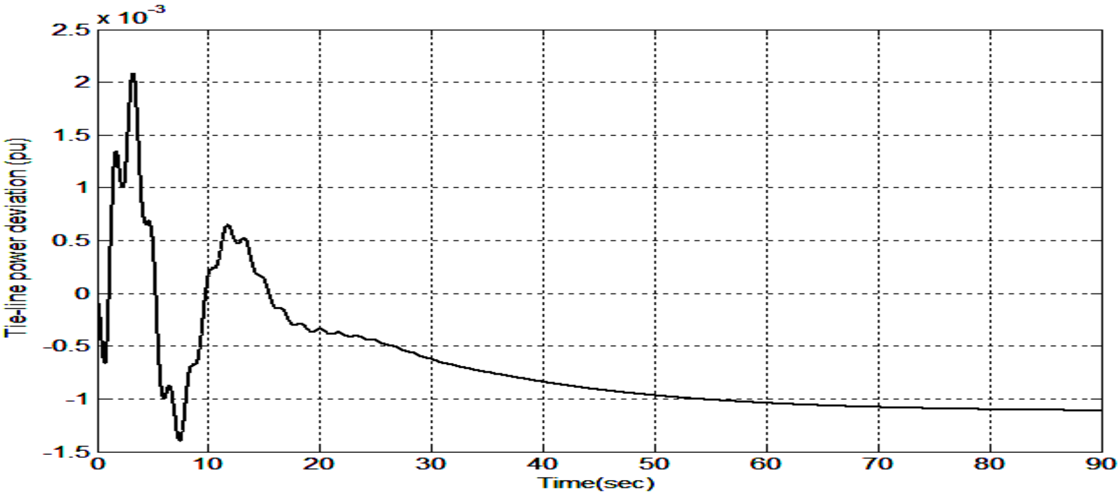


Figure 4.10: Dynamic tie-line$_{12}$ power response integrated with TCPS-SC unit

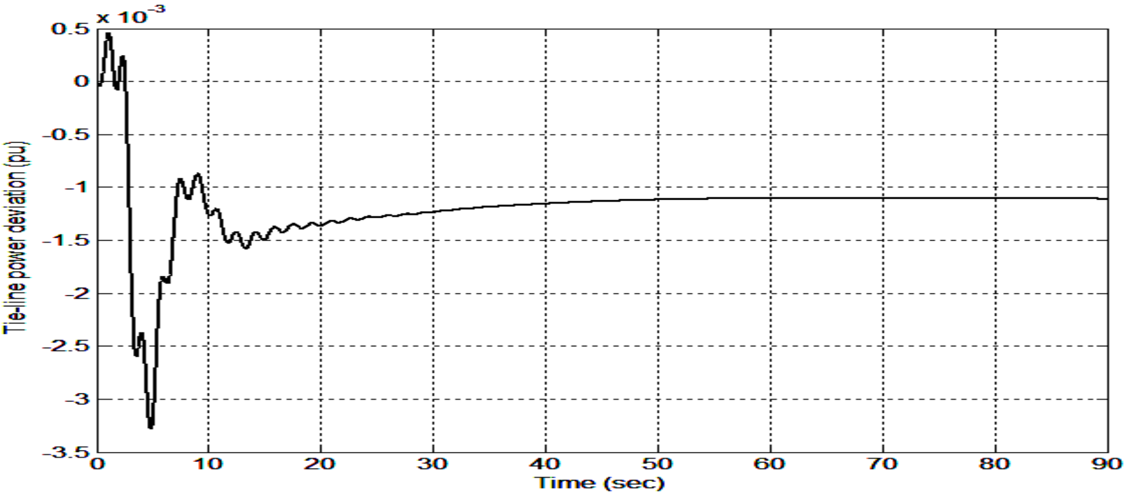


Figure 4.11: Dynamic tie-line$_{23}$ power response integrated with TCPS-SC unit

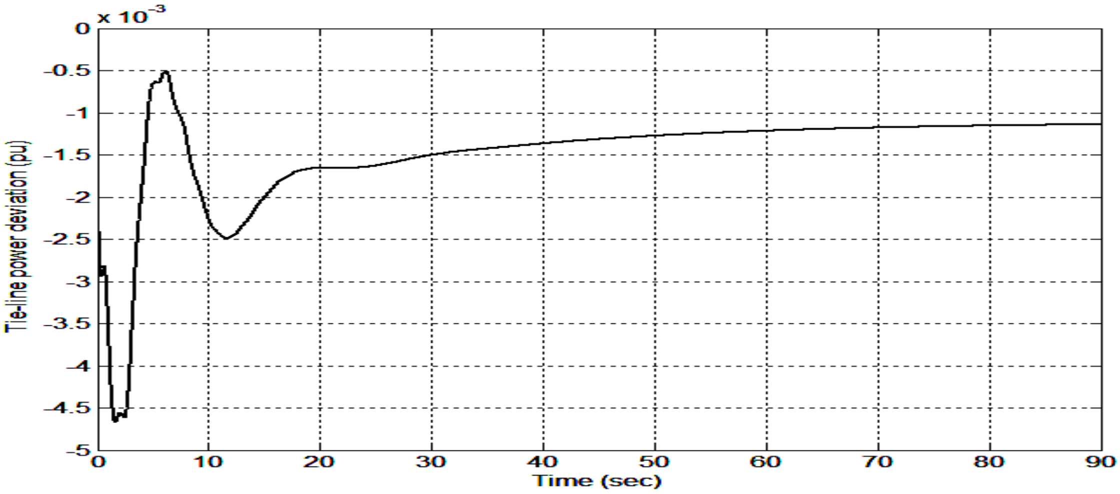


Figure 4.12: Dynamic tie-line$_{31}$ power response integrated with TCPS-SC unit

TABLE 4.4: Frequency response characteristics with TCPS-SC unit

	Settling time (sec)			**Peak over/undershoot (pu)**		
	Area1 Δf_1	**Area2** Δf_2	**Area3** Δf_3	**Area1** Δf_1	**Area 2** Δf_2	**Area3** Δf_3
With TCPS-SC Unit	28	29	19	-0.212	-0.531	-0.527

TABLE 4.5: Tie-line power response characteristics with TCPS-SC unit

	Settling time (sec)			**Peak over/undershoot (pu)**		
	ΔP_{12}	ΔP_{23}	ΔP_{31}	ΔP_{12}	ΔP_{23}	ΔP_{31}
With TCPS-SC Unit	10	15	20	.0.002	-0.003	-0.004

Figures 4.7-4.12 represents the dynamic frequency and tie-line power response of three-area DHPS integrated with TCPS-SC unit. Dynamic frequency response of the three-area hybrid power system is shown in Figures 4.7-4.9. The frequency deviation diminishes to zero in near about 28 seconds in area-1, 29 seconds and 19 seconds in area-2 and area-3 respectively. Each DISCO demands 0.1p.u more than the normal load demand. This causes fluctuation in frequency due to unbalance of power demand and power generation. To restore frequency to its normal value, LFC comes into action. Power generation of each GENCO increases to match the load demand and generation according to the contract. The tie-line power dynamics are shown in Figures 4.10-4.12. Due to incremental load change of each DISCO, every GENCO participates in it. Every DISCO takes power from each GENCO in its own area and from other areas according to the cpf's. Frequency deviations and tie-line power deviations are evaluated in terms of settling time, over/undershoot which are depicted in Tables 4.4 and 4.5. It is observed that frequency and tie-line power deviations die out quickly with integration of TCPS-SC combination.

Table 4.6: Gains of PID controller with TCPS-SC unit

Controller	K_p	Ki	K_d
PID 1	0.52	-0.81	0.03
PID 2	6.94	0.61	-9.24
PID 3	0.31	0.72	0.18
PID 4	8.83	7.98	7.71
PID 5	0.32	-0.81	0.03
PID 6	7.72	1.08	-16.32

4.1.3 A Comparative Study- without and with TCPS-SC unit

Here, a comparative analysis without and with TCPS-SC unit is presented. Simulation result reveals that there is improvement in frequency deviation profile with the integration of TCPS-SC unit in the power system. Comparative simulation results are shown below.

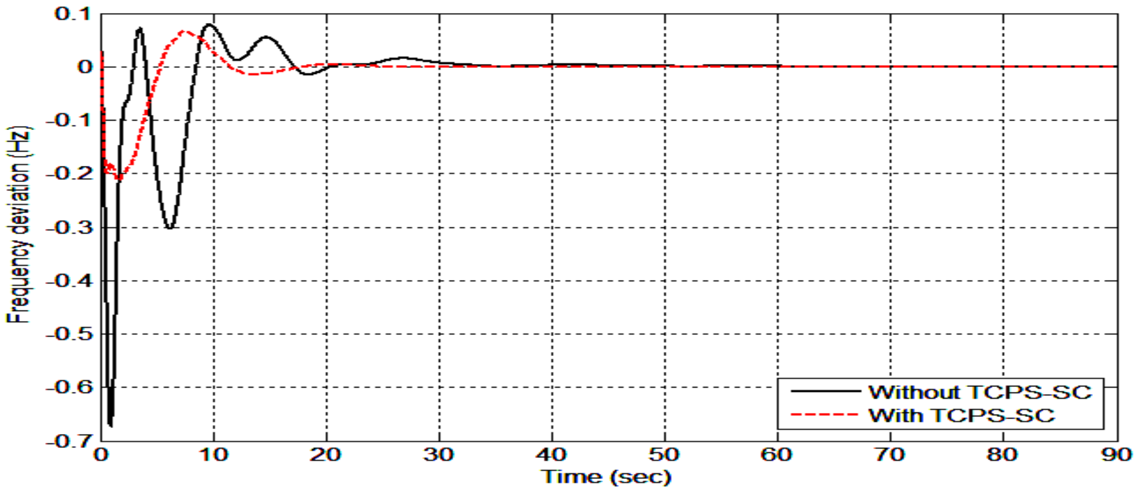


Figure 4.13: Dynamic frequency response of area-1 without and with TCPS-SC unit

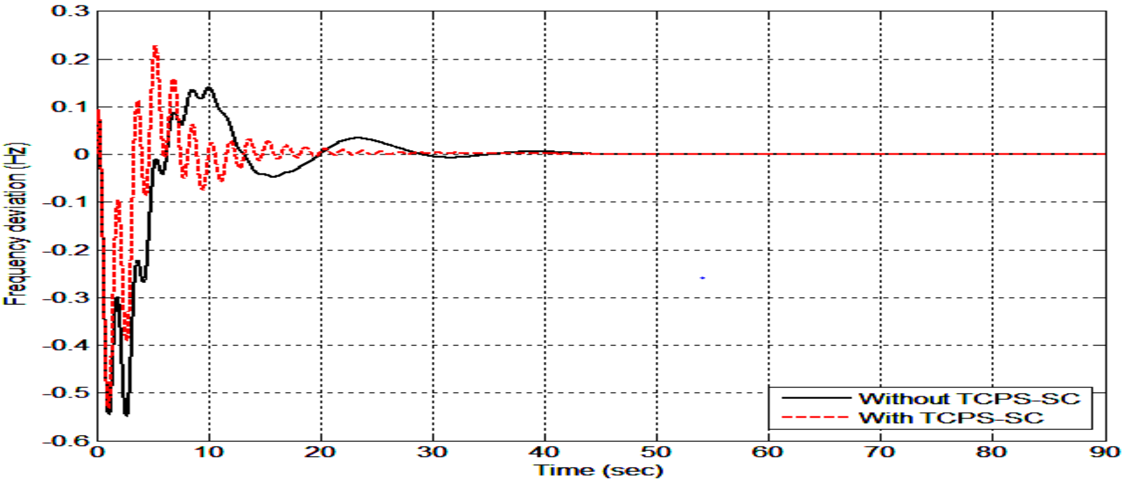


Figure 4.14: Dynamic frequency response of area-2 without and with TCPS-SC unit

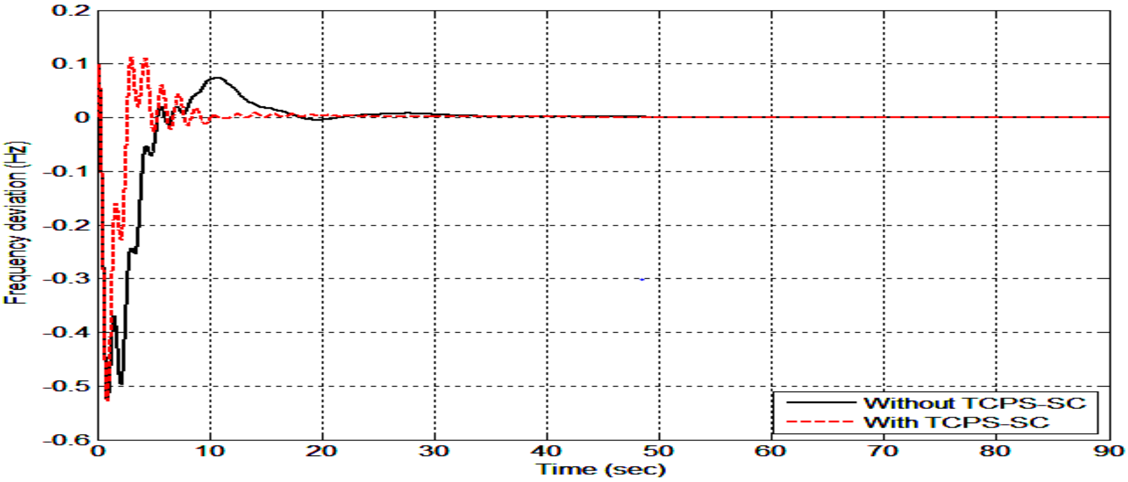


Figure 4.15: Dynamic frequency response of area-3 without and with TCPS-SC unit

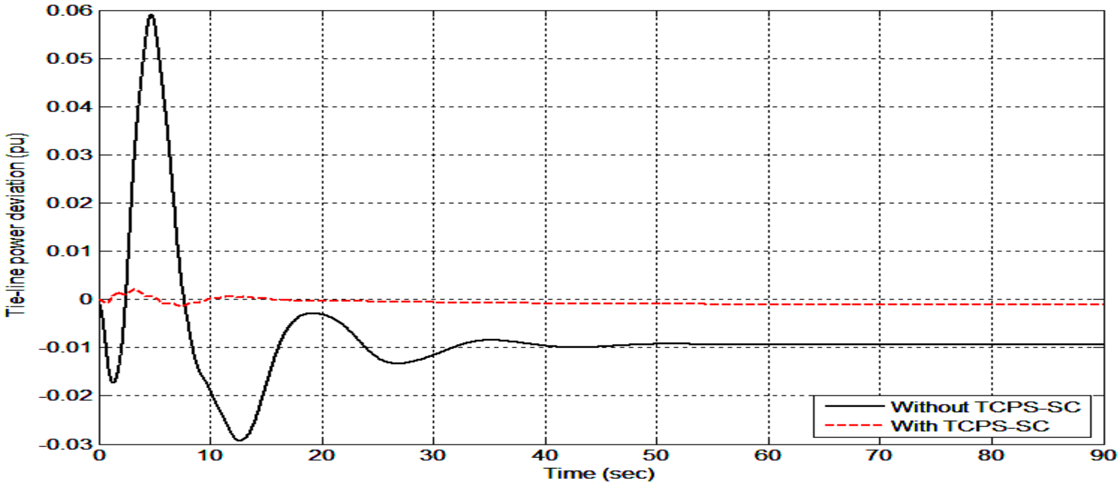


Figure 4.16: Dynamic tie-line$_{12}$ power response without and with TCPS-SC unit

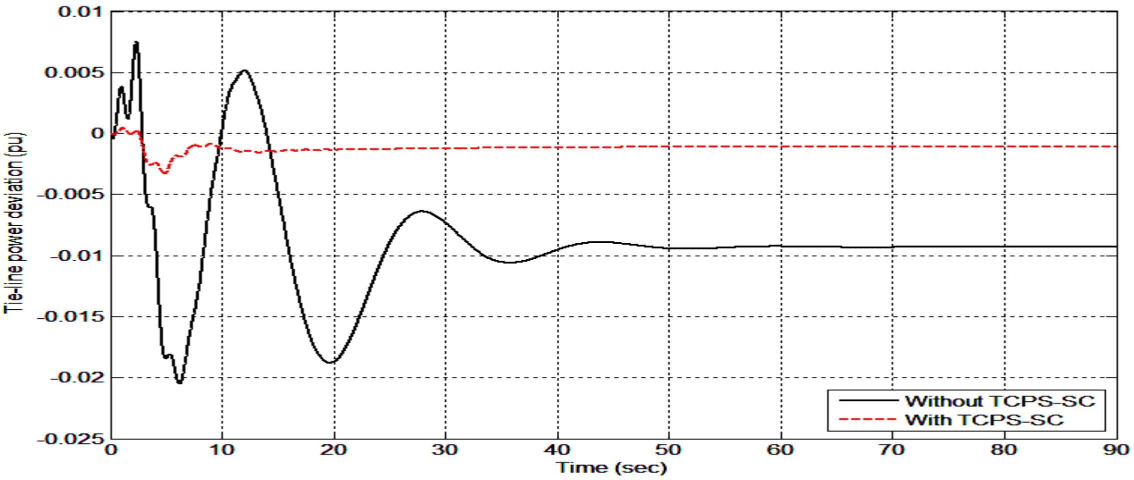


Figure 4.17: Dynamic tie-line$_{23}$ power response without and with TCPS-SC unit

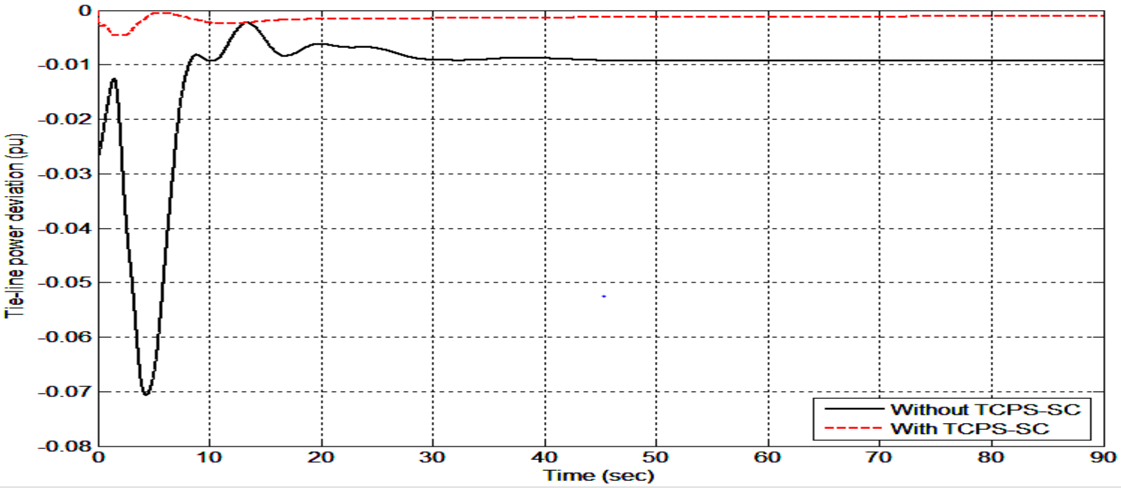


Figure 4.18: Dynamic tie-line$_{31}$ power response without and with TCPS-SC unit

TABLE 4.7: Comparative frequency response without & with TCPS-SC unit

	Settling time (sec)			**Peak over/undershoot (pu)**		
	Area1 Δf_1	**Area2 Δf_2**	**Area3 Δf_3**	**Area1 Δf_1**	**Area 2 Δf_2**	**Area3 Δf_3**
Without TCPS-SC	34	44	35	-0.697	-0.555	-0.543
With TCPS-SC	28	29	19	-0.212	-0.531	-0.527

TABLE 4.8: Comparative tie-line power response without & with TCPS-SC unit

	Settling time (sec)			**Peak over/undershoot (pu)**		
	ΔP_{12}	ΔP_{23}	ΔP_{31}	ΔP_{12}	ΔP_{23}	ΔP_{31}
Without TCPS-SC	50	60	40	0.059	-0.021	-0.071
With TCPS-SC	10	15	20	0.002	-0.003	-0.004

Figures 4.13-4.18 presents the comparative analysis of integrating and without integrating TCPS-SC unit in the DHPS. Comparative analysis in terms of settling time, peak over/undershoot is presented in Tables 4.7 and 4.8. It can be seen clearly that integration of TCPS-SC unit improves the LFC performance.

4.2 Frequency and Tie–Line Power Dynamics of Two-Area DHPS due to Sudden Load Increment

In this case LFC scheme is implemented on a two-area DHPS. Various nonlinearities and time delay in communication channel is taken into account. BELBIC controller is used for the implementation of LFC scheme and comparison with other controllers is also presented. Bilateral contract scenario has been considered wherein all the areas have unequal shares in the generation process as defined by the following DPM:

$$\text{DPM} = \begin{pmatrix} 0.3 & 0.3 & 0.2 & 0.2 \\ 0.2 & 0.2 & 0.2 & 0.1 \\ 0.1 & 0.1 & 0.1 & 0.1 \\ 0.2 & 0.2 & 0.3 & 0.3 \\ 0.1 & 0.1 & 0.1 & 0.2 \\ 0.1 & 0.1 & 0.1 & 0.1 \end{pmatrix} \tag{4.2}$$

Each Disco demands 0.02 pu MW total power from GENCOs as defined by entries in DPM and each GENCO participate in AGC as defined by following apf's:

$apf_1 = 0.5$, $apf_2 = 0.35$, $apf_3 = 0.15$, $apf_4 = 0.5$, $apf_5 = 0.35$, $apf_6 = 0.15$

$GENCO_1$ (scheduled)

$\Delta P_{g1} = (0.3+0.3+0.2+0.2)*0.02$

$= 0.02$pu MW

Similarly,

$\Delta Pg_2 = 0.014$pu MW

$\Delta Pg_3 = 0.008$pu MW

$\Delta Pg_4 = 0.02$pu MW

$\Delta Pg_5 = 0.01$pu MW

$\Delta Pg_6 = 0.008$pu MW

Scheduled tie-line power flow from area-1 to area-2

$\Delta P_{tie12,sch}$ = Demand of DISCOs in area-2 from GENCOs in area-1 – Demand of DISCOs in area-1from GENCOs in area-2

$$= (cpf_{13} + cpf_{23} + cpf_{33})\Delta P_{L3} + (cpf_{14} + cpf_{24} + cpf_{34})\Delta P_{L4} - (cpf_{41} + cpf_{51} + cpf_{61})\Delta P_{L1} + (cpf_{42} + cpf_{52} + cpf_{62})\Delta P_{L2}$$

$$= (0.2 + 0.2 + 0.1 + 0.2 + 0.1 + 0.1)* 0.02 - (0.2 + 0.1 + 0.1+ 0.2 + 0.1 + 0.1)* 0.02$$

$$= 0.018 - 0.016$$

$$= 0.002\text{pu MW}$$

4.2.1 Case 1: Effect of nonlinearities and time delay

In this case the effect of various nonlinearities (GRC, GDB) and time delay in communication channel is presented.

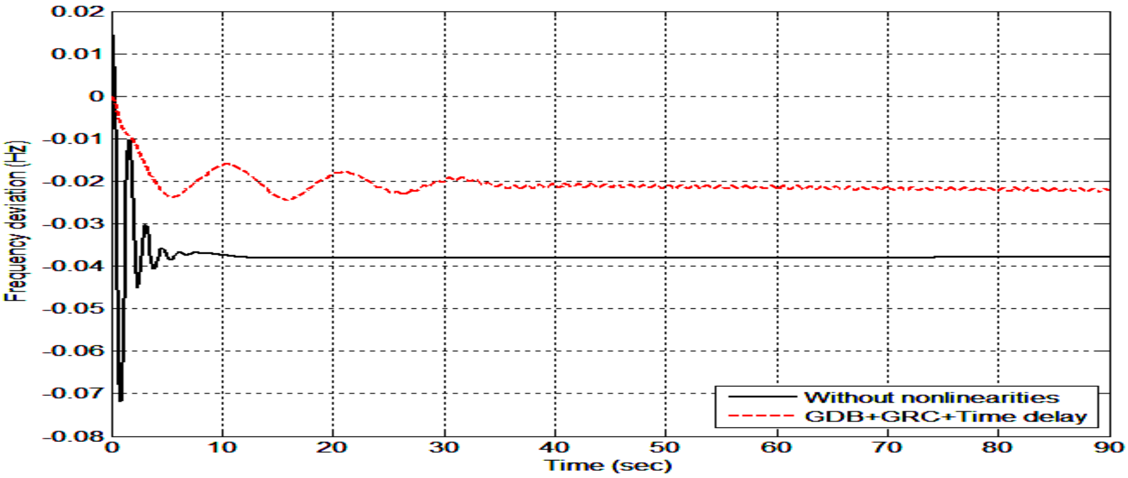


Figure 4.19: Dynamic frequency response of area-1 without and with nonlinearities, time delay in communication channel

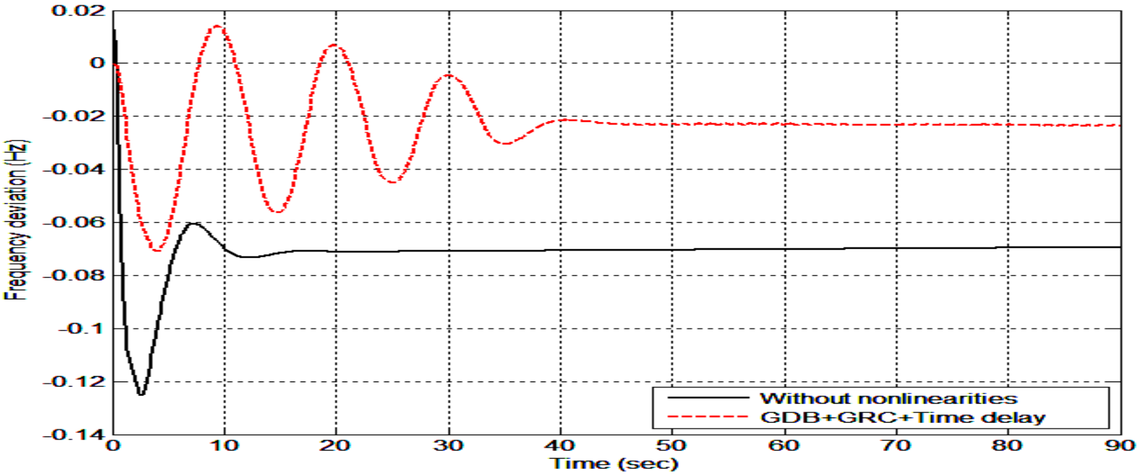


Figure 4.20: Dynamic frequency response of area-2 without and with nonlinearities, time delay in communication channel

Figures 4.19 and 4.20 show the effect of nonlinearity constraints like GDB, GRC and time delay in communication channel on the frequency response of the power system. The frequency response of the power system gets distorted and settling time increases when GDB, GRC and time delay in communication channel is taken into account.

4.2.2 Case 2: Frequency and tie-line power response without considering intermittency in solar power with different controllers

In this case no intermittency in solar power is considered. Comparative results of various controllers in mitigating frequency and tie-line power oscillation is presented.

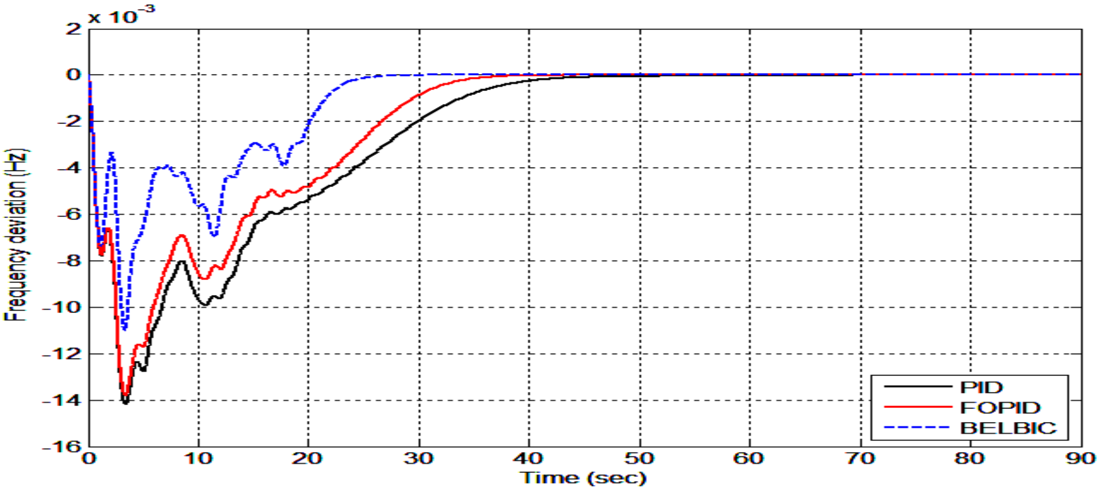


Figure 4.21: Dynamic frequency response of area-1 with different controllers

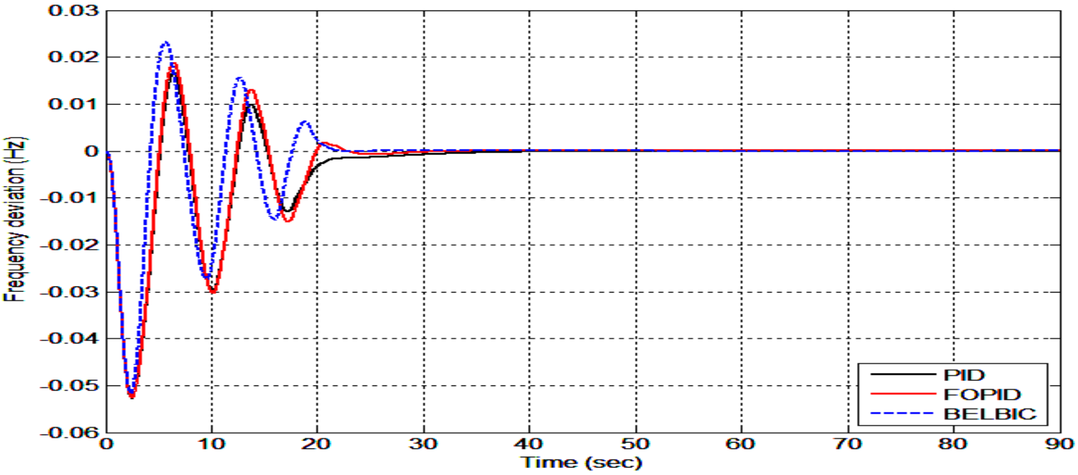


Figure 4.22: Dynamic frequency response of area-2 with different controllers

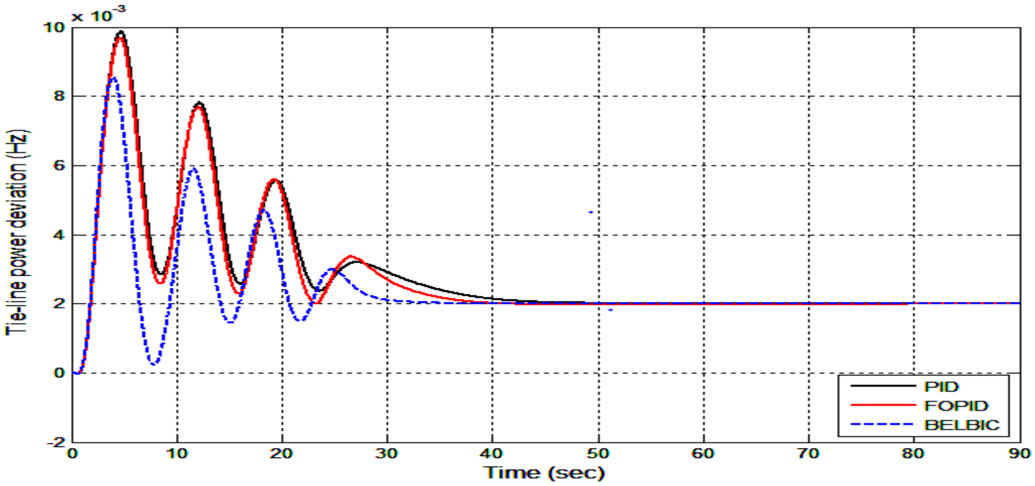


Figure 4.23: Dynamic tie-line power response with different controllers

TABLE 4.9: Comparative frequency response of different controllers

Controllers	**Settling time (sec)**		**Peak over/undershoot (pu)**	
	Δf_1 Area 1	**Δf_2 Area 2**	**Δf_1 Area 1**	**Δf_2 Area 2**
PID	43	38	-0.0142	-0.0527
FOPID	36	32	-0.0138	-0.0523
BELBIC	27	22	-0.0111	-0.0516

TABLE 4.10: Comparative tie-line power response of different controllers

Controllers	**Settling time (sec)** **ΔP_{tie12}**	**Peak over/undershoot (pu)** **ΔP_{tie12}**
PID	45	0.0099
FOPID	38	0.0097
BELBIC	32	0.0083

Frequency and tie-line power deviations without considering any intermittency in solar power with different controllers are shown in Figures 4.21-4.23. Complete analysis of each controller in terms of peak over/undershoot and settling time is given in Tables 4.9 and 4.10. It shows that BELBIC controller is quite effective in mitigating frequency and tie-line power deviations.

TABLE 4.11: Various controllers parameter

PID 1	PID 2	FOPID 1	FOPID 2	BELBIC 1	BELBIC 2
$K_p = 0.02$	$K_p = 0.015$	$K_p = -0.013$	$K_p = -0.323$	$K_1 = 3$	$K_1 = 2$
$K_i = -1.2$	$K_i = -0.185$	$K_i = -1.4$	$K_i = -0.2$	$K_2 = 1$	$K_2 = 6$
$K_d = 0.009$	$K_d = 0.561$	$K_d = -0.015$	$K_d = - 0.032$	$K_3 = 5$	$K_3 = 40$
		$\lambda = 0.975$	$\lambda = 0.126$	$K_4 = 325$	$K_4 = 25$
		$\mu = 0.982$	$\mu = 0.300$	$K_5 = 0.001$	$K_5 = 5$
				$\alpha = 0.5$	$\alpha = 0.72$
				$\beta = 0.5$	$\beta = 0.65$

4.2.3 Case 3: Frequency and tie-line power response considering 2% random variations in solar power with different controllers

In this case random variations in solar power are considered. Comparative results of various controllers in mitigating frequency and tie-line power oscillations considering 2% intermittency in solar power is presented.

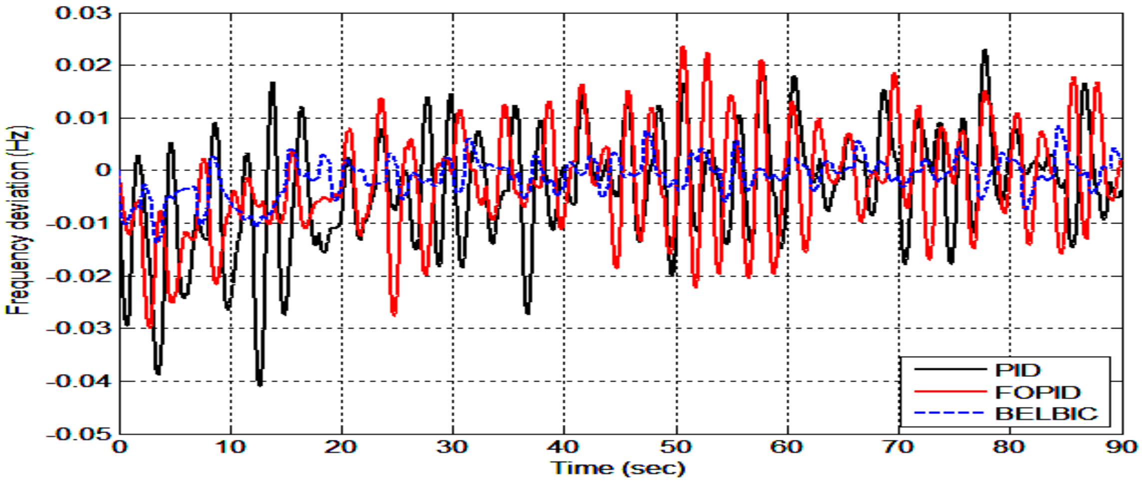


Figure 4.24: Dynamic frequency response of area-1 for 2% intermittency in solar power with different controllers

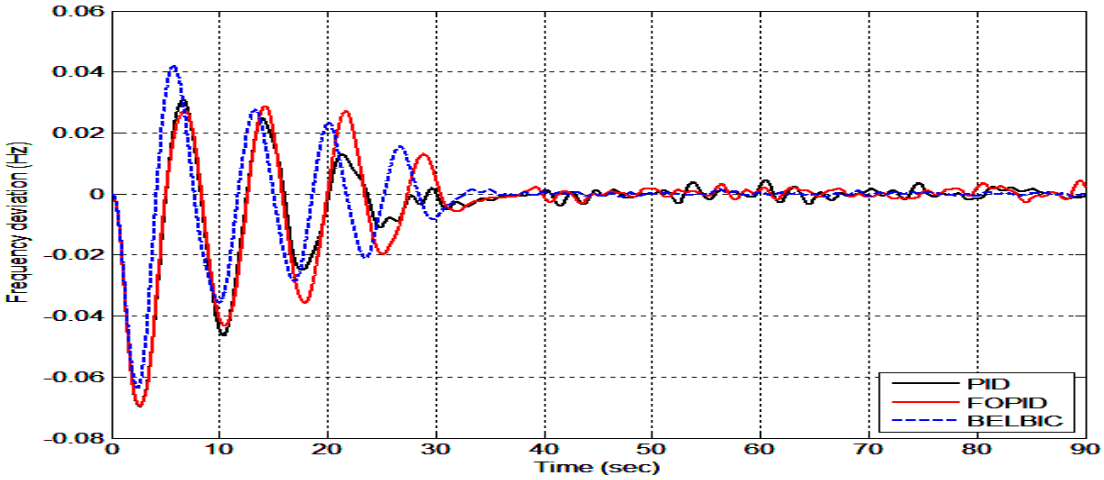


Figure 4.25: Dynamic frequency response of area-2 for 2% intermittency in solar power with different controllers

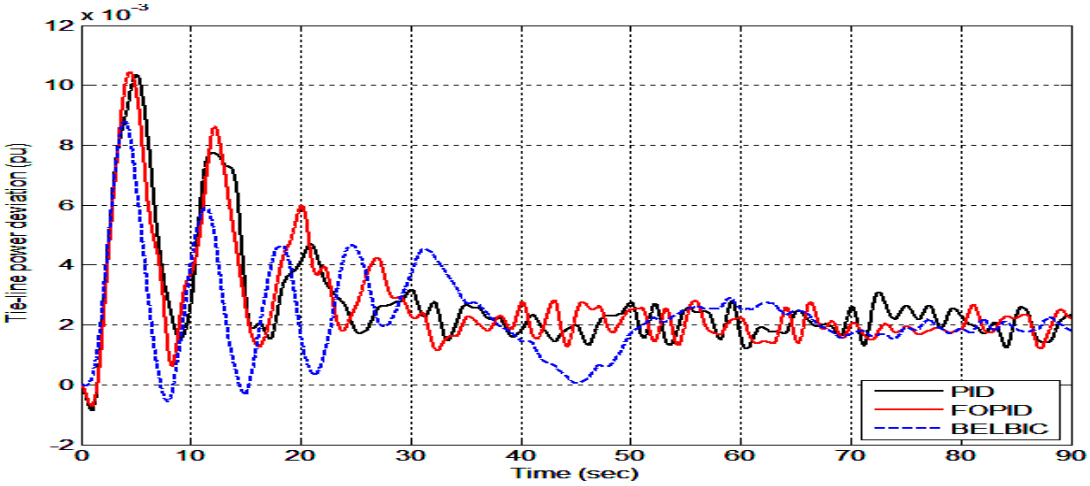


Figure 4.26: Dynamic tie-line power response for 2% intermittency in solar power with different controllers

considering intermittency in solar power. Results obtained clearly shows that BELBIC controller is quite effective in diminishing frequency and tie-line power deviations considering random variations in solar power as compared to PID, FOPID.

4.3 SENSITIVITY ANALYSIS

Sensitivity analysis is carried to test the robustness of various controllers against system parameter and operating load variations. The governor time constant (T_{gi}) is reduced by −50% and the operating load of the system is increased by +10%.

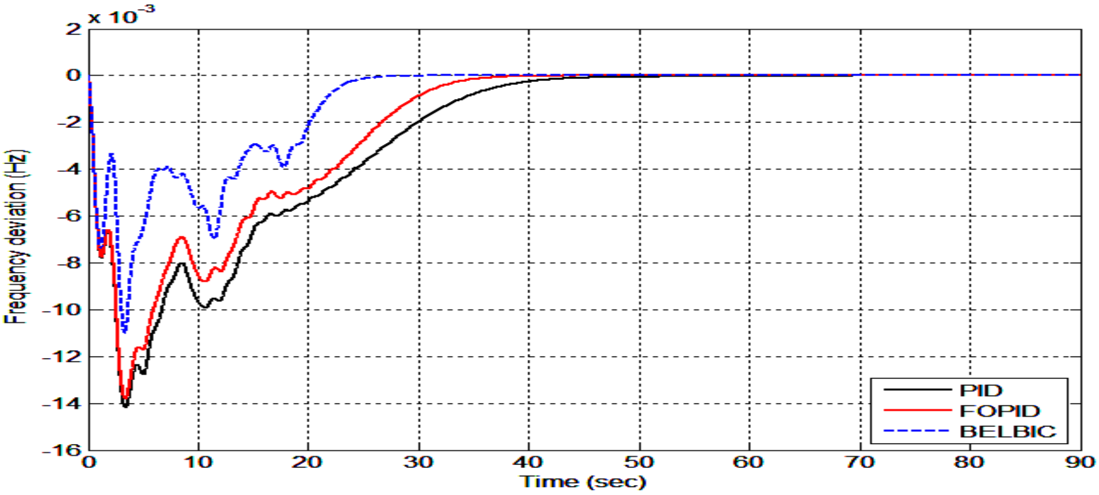


Figure 4.27: Dynamic frequency response of area-1 with different controllers for −50 variation in Tg_1

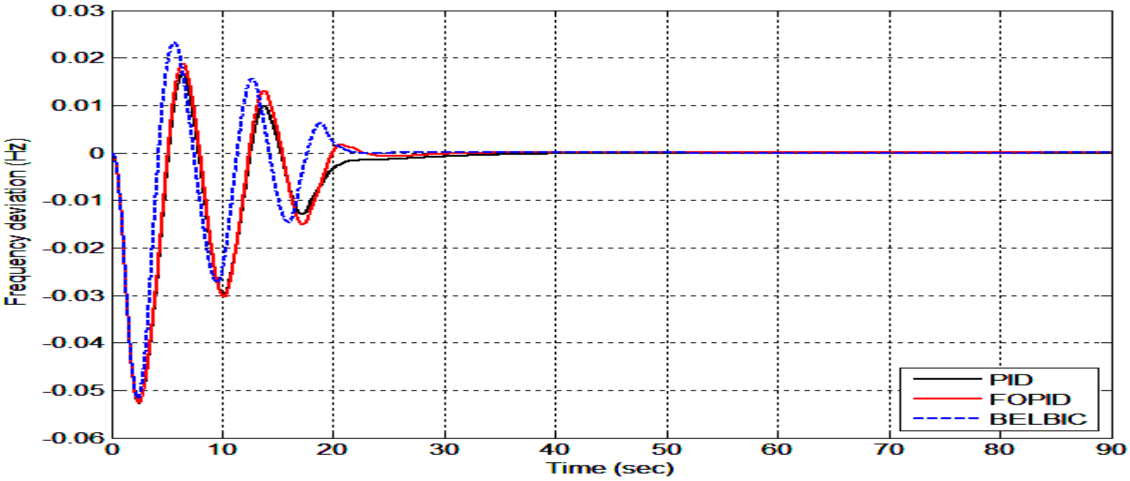


Figure 4.28: Dynamic frequency response of area-2 with different controllers for −50% variation in Tg_1

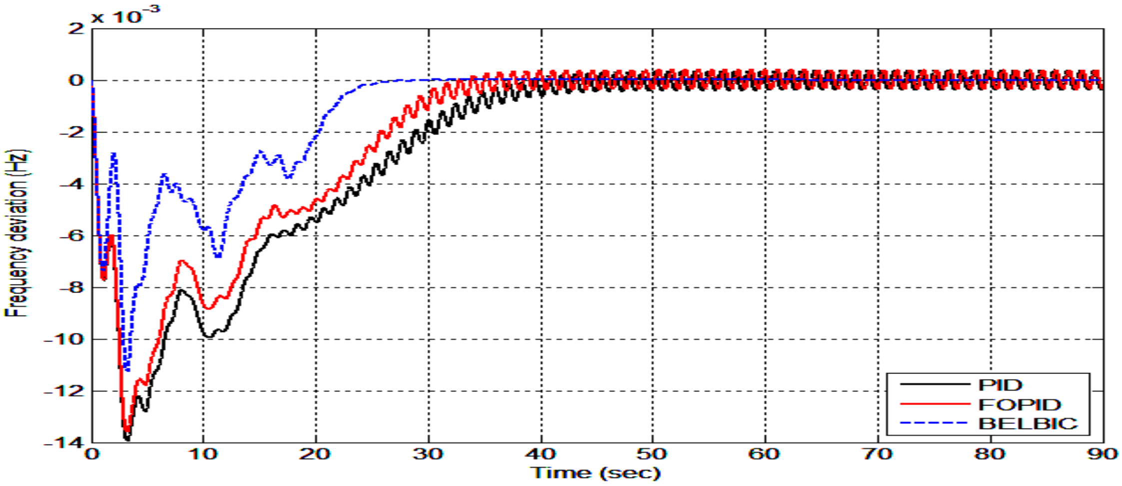


Figure 4.29: Dynamic frequency response of area-1 with different controllers for 10% increase in load

Figures 4.27, 4.28 present the dynamic frequency and tie-line power response corresponding to -50% variation in governor time constant (T_{g1}) with different controllers. It shows that BELBIC controller can handle system parameter variations quite effectively as compared to PID, FOPID. Figure 4.29 shows the effect of changing operating load conditions (+10%) on frequency response of area-1. The dynamic frequency response gets distorted in the case of PID, FOPID controller but the frequency response remains stable in the case of BELBIC controller which shows the robustness of BELBIC controller.

CHAPTER 5
CONCLUSIONS AND FUTURE SCOPE

5.1 Summary

This thesis mainly contributes in the area of LFC of multi-area DHPS incorporating various DG sources and EV’s. Various DG sources like solar PV, FC, DEG and biomass based HDGT are made to participate in LFC along with proper choice of back-up sources to offset the intermittency. Effect of TCPS-SC unit in improving LFC performance is analyzed. To make it more realistic, effect of various nonlinearity constraints and time delay in communication channel is also considered. Various control strategies are implemented and their comparative results are also presented.

In this thesis, essentially, two different power system configurations are analyzed. Configuration-1 consists of a three-area DHPS. DG energy sources like solar PV, FC, DEG and biomass based HDGT participates in LFC along with the conventional thermal, hydro unit. BESS is used to handle intermittency of solar power. TCPS-SC unit included in the power system helps to improve the LFC performance. The performance of the developed DHPS is investigated by using PID controller.

Configuration-2 of the DHPS consists of DG sources like solar PV and biomass based HDGT. EVs are used to handle intermittency of solar power. To make it more realistic, effect of nonlinearity constraints and time delay in communication channel is also considered. The performance of the developed DHPS is investigated by using PID, FOPID and BELBIC controller. A comparative study of effectiveness of all the controllers in improving frequency profile is carried out in the presence of various nonlinearity constraints. BELBIC controller is found to be more effective to deal with various LFC issues. Sensitivity Analysis validates the robustness of the BELBIC controller against system imperfections and occurrence of uncertainties.

5.2 Conclusions

LFC strategy is successfully implemented to two different power system configurations which are characterized by high penetration of DG energy resources and also EVs to eradicate intermittency of renewable energy power sources. To integrate a higher share of RES, the electrical infrastructure and energy systems should be made flexible and intelligent. EVs together with renewable energy sources provide sustainable mobility to the electrical power system. Even help to decarbonise the environment. Simulation results show that appropriate combination of FACTS device with external ESS helps to improve the frequency profile of the power system. The effect of various nonlinearities and time delay in communication channel can be efficiently dealt with the implementation of BELBIC. BELBIC is capable of handling system imperfections and occurrence of uncertainties in the power system in a better way as compared to PID, FOPID.

5.3 Future Scope

Research and development is a continual and a never-ending process. Any research work already carried out, there is always a scope of progress and many areas open up for carrying out more research work. As a result of the investigations carried out in the present thesis, following aspects are recognized with future research scope.

- In this present work the load disturbances are taken as deterministic (static) in nature. So, in future the work could be extended to time varying (dynamic) load disturbances.
- The study can be further extended for increased number of interconnected areas.
- This thesis presented and proposed for only active power controls of various DG energy resources and EVs for LFC. But in real time when there is a power disruption both the voltage and frequency fluctuates occur, so the use of reactive power to stabilize the system has to be done in future by using intelligent control methods.
- Use of optimization techniques like Particle swarm optimization, Grey wolf optimization, Firefly Algorithm, Genetic Algorithm etc. to tune controller’s parameters.
- LFC with different FACTS devices such as UPFC, IPFC etc. Use of versatile FACTS devices will enhance system performance considerably.

APPENDIX

f	50 Hz
R_1, R_2, R_3	2.4Hz/pu MW
B_1, B_2, B_3	0.425 pu MW/Hz
T_{g1}, T_{g2}, T_{g3}	0.08s
T_{t1}, T_{t2}, T_{t3}	0.3s
K_{ps1}, K_{ps2}, K_{ps3}	120Hz/pu MW
T_{ps1}, T_{ps2}, T_{ps3}	20s
T_{12}, T_{23}, T_{13}	0.0866s
K_p,K_i,K_d	Gain of hydraulic PID governor, K_p =26, K_i =5.0, K_d =4.0
$P_{tie,max}$	200MW (Maximum tie-line Power)
K_{PV}	1
T_{PV}	1.8s
K_{BESS}	-1/300
T_{BESS}	0.1s
K_{FC}	0.01
T_{FC}	4.0s
K_{AE}	0.002
T_{AE}	0.05s
K_{DEG}	1/300
T_{DEG}	2s
K_{EV}	1
T_{EV}	1s
a_{12}, a_{23}, a_{31}	-1
K_{SC}	0.7
T_{SC}	0.01s
K_{TCPS}	1.5
T_{TCPS}	0.1s
GDB	± 0.036Hz
GRC	0.0005 pu MW/min
Time Delay	0.4s
P_{r1}, P_{r2}, P_{r3} (Conf.-1) P_{r1}, P_{r2} (Conf.-2)	600MW each 800MW each

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LIST OF PUBLICATIONS

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