Effects of Availability Based Tariff on Secondary Frequency Control and Tieline Power Flow of Interconnected Hybrid Power System

Thesis

Submitted by

Gargi Konar

Doctor of Philosophy (Engineering)

Department of Power Engineering
Faculty Council of Engineering & Technology
Jadavpur University
Saltlake Campus
Kolkata – 700106, India

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JADAVPUR UNIVERSITY

KOLKATA – 700032, INDIA

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1. **Title of the thesis:** Effects of Availability Based Tariff on Secondary Frequency Control and Tieline Power Flow of Interconnected Hybrid Power System

2. **Name, Designation And Institution of the Supervisors:**

   1. **Prof. Niladri Chakraborty**
      Professor
      Department of Power Engineering
      Jadavpur University
      Salt Lake Campus, Block – LB, Plot – 8,
      Sector III, Salt Lake
      Kolkata – 700106
      West Bengal, India

   2. **Prof. Kamal Krishna Mandal**
      Professor
      Department of Power Engineering
      Jadavpur University
      Salt Lake Campus, Block – LB, Plot – 8,
      Sector III, Salt Lake
      Kolkata – 700106
      West Bengal, India

3. **List of Journal Publications:**

[1] G. Konar, N. Chakraborty, K. K. Mandal, Hybrid renewable energy-integrated Indian power system under availability-based tariff, International Transactions on Electrical Energy Systems, 29(9) (2019). http://dx.doi.org/10.1002/2050-7038.12162.

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Presented all the Conference papers listed above (5) as the First author.

STATEMENT OF ORIGINALITY

I, Gargi Konar, registered on 02.08.2017 do hereby declare that this thesis entitled **"Effects of Availability Based Tariff on Secondary Frequency Control and Tieline Power Flow of Interconnected Hybrid Power System"** contains literature survey and original research work done by the undersigned as part of the Doctoral studies. All information in this thesis has been obtained and presented in accordance with the existing academic rules and ethical conduct. I declare that, as required by this rules and conduct, I have hereby fully cited and referred all materials and results that are not original to this work. I also declare that I have checked this thesis as per the "Policy on Anti Plagiarism, Jadavpur University, 2019, and the level of similarity as checked by iThenticate Software is 3%".

Gargi Konar

Signature of the candidate
Date: 14.08.23
Certified by the Supervisors:

Niladri Chakraborty 14/8/23

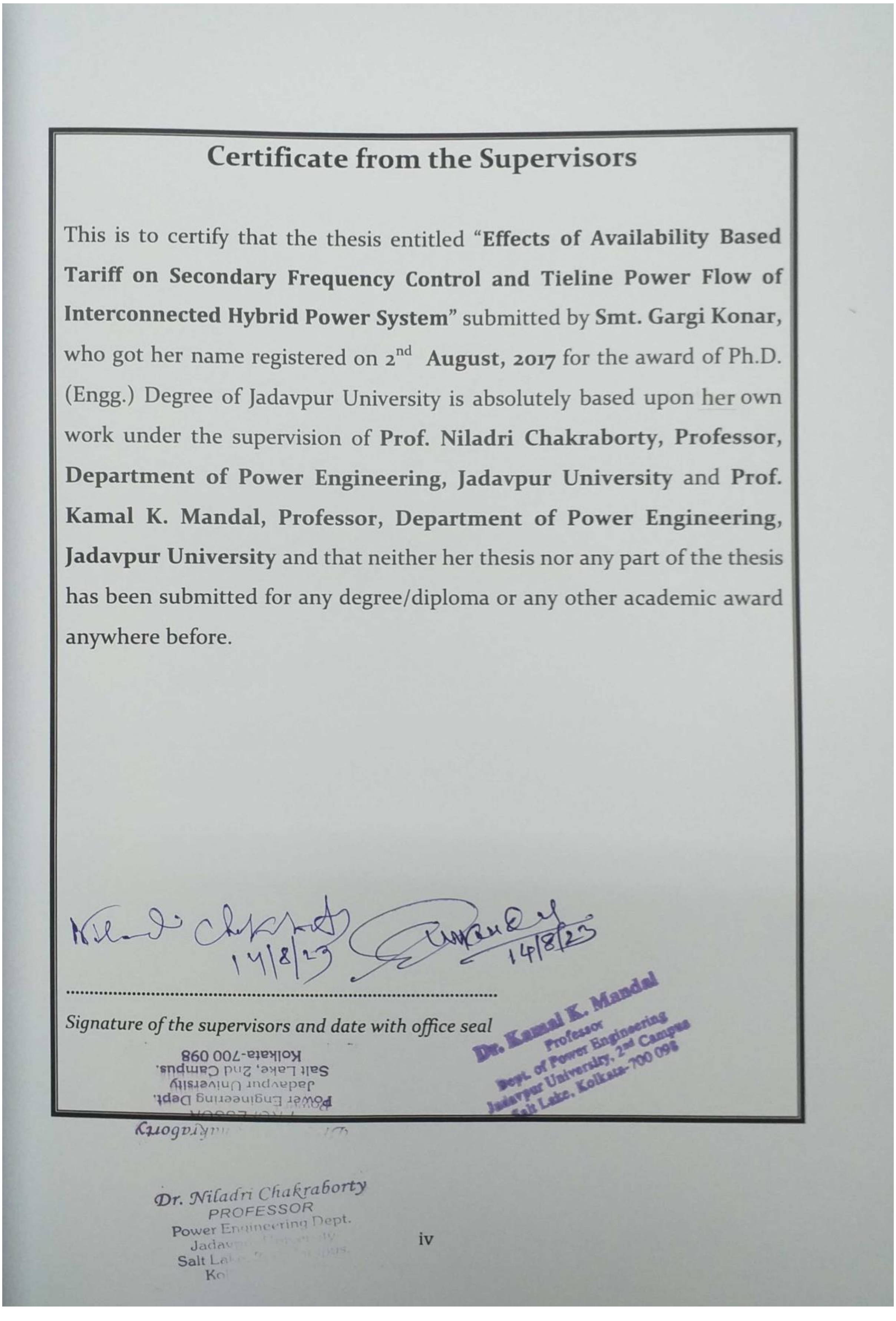
Prof. Niladri Chakraborty
Professor
Department of Power Engineering
Jadavpur University

Dr. Niladri Chakraborty
PROFESSOR
Power Engineering Dept.
Jadavpur University
Salt Lake, 2nd Campus
Kolkata 700 09

14/8/23

Prof. Kamal K. Mandal
Professor
Department of Power Engineering
Jadavpur University

Dr. Kamal K. Mandal
Professor
Dept. of Power Engineering
Jadavpur University, 2nd Campus
Salt Lake, Kolkata-700 098



Certificate from the Supervisors

This is to certify that the thesis entitled "**Effects of Availability Based Tariff on Secondary Frequency Control and Tieline Power Flow of Interconnected Hybrid Power System**" submitted by **Smt. Gargi Konar,** who got her name registered on 2nd **August, 2017** for the award of Ph.D. (Engg.) Degree of Jadavpur University is absolutely based upon her own work under the supervision of **Prof. Niladri Chakraborty, Professor, Department of Power Engineering, Jadavpur University** and **Prof. Kamal K. Mandal, Professor, Department of Power Engineering, Jadavpur University** and that neither her thesis nor any part of the thesis has been submitted for any degree/diploma or any other academic award anywhere before.

Niladri Chakraborty 14/8/23

14/8/23

....

Signature of the supervisors and date with office seal

Dr. Kamal K. Mandal
Professor
Dept. of Power Engineering
Jadavpur University, 2nd Campus
Salt Lake, Kolkata- 700 098

Dr. Niladri Chakraborty
PROFESSOR
Power Engineering Dept.
Jadav
Salt La
Ko

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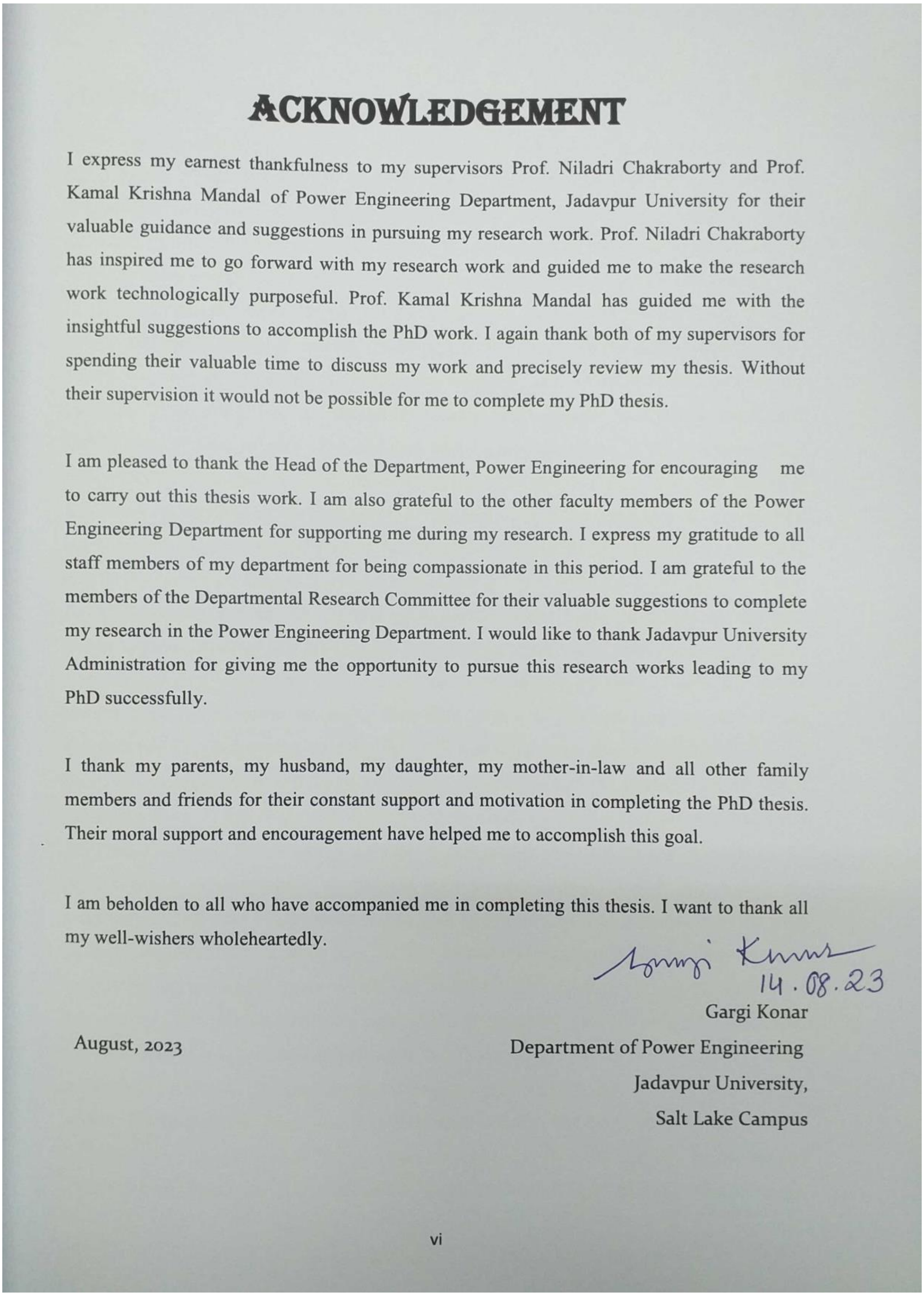
Dedicated

To

My Parents



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14.08.23

Gargi Konar
Department of Power Engineering
Jadavpur University,
Salt Lake Campus

August, 2023

Abstract

In the last two decades power sector has been modernized through newer, better and safer technologies. There are lots of changes starting from its restructuring, application of information technology and digital communication, incorporation of renewable energy resources, smart metering etc in the power system operation. Nowadays interconnected power systems operate country wise. In such situation frequency regulation has become one of the most focused issues in power system operation. In the restructured power system, private and public power producers, distributers participate in a competitive power market. Hence it is very much needed to maintain the frequency at a set value as well as keep the economy of the power trading sustainable. To keep both regulated, availability based tariff (ABT) can provide a solution. The deviation of the actual generation of the generators from their availability i.e. their declared generation can good impact on the frequency fluctuation if the excess generation or the deficiency of generation is either incentivised or penalised depending on the grid frequency status. Such frequency linked pricing criterion has been used here in the secondary frequency control loop of the different proposed interconnected hybrid power generating system. The thermal-hydro-diesel/biomass based three area or four area power system connected through tie-lines are tested for sudden load perturbations. Instead of conventional area control error (ACE) based secondary frequency control scheme, generation control error (GCE) based secondary frequency control scheme has been adopted for six different MATLAB/Simulink models. The GCE signal has been generated following the UI price rate as imposed by electricity regulatory commission and the deviation of the actual generation from its declared value. It is also depended on the deviation of the grid frequency from the set value of the frequency. One of the case studies includes the wind generation. As its availability is intermittent, it operates only on the primary control loop not in the secondary control loop which works on the basis of availability. The penetration of the wind power is also studied in another case. Particle swarm optimization (PSO) has been used for optimizing the controller gains which has improved the transient frequency, generation deviation and the tie line power plots significantly. The settling time has reduced a lot. Lastly, incorporation of a microgrid comprising fuel cell, offshore wind turbine generators, diesel generators along with flywheel energy storage system (FESS) and battery energy storage system (BESS) in the three area interconnected system has been studied for the load perturbations. The results show that the incorporation of wind or microgrid does not hamper the frequency regulation if the controller gains are chosen appropriately. Moreover the

unscheduled interchange costs can be kept within 1780 Rs./MWHr and 0 INR/MWHr for frequency limit of 50.00 Hz to 50.03 Hz. It is observed that the application of UI based pricing in the ABT regime can be well appreciated for the interconnected power systems comprising conventional and renewable energy resources. The grid discipline in terms of the frequency regulation and the generation control can be maintained with the proposed attempt. To solve these cases, interconnected power system models have been developed in-house and simulated in MATLAB/Simulink platform. MATLAB script has been written for PSO program to optimise the PI controller gains and feed it to the Simulink model. Several iterations are required to run both the Simulink model and the MATLAB script in an interlinked manner which took some computational time.

The work done in this thesis can contribute to achieve the Sustainable Development Goals (SDGs) viz. SDG 7 and SDG 13. The frequency regulation attained here under unscheduled interchange (UI) price based secondary frequency control scheme, finally leads to control the generation and consumption of electricity. Thus, the fuel brunt can be optimized for the conventional generators catering the base load of an interconnected power system which can reduce the cost of electricity generation and in turn it can make the electrical energy affordable worldwide. Again the integration of the wind, biomass, fuel cell and the energy storage systems in the interconnected power system facilitates green power generation. Hence this research work can help to attain the sustainable, affordable electrical energy which belong to the sustainable development goal 7. Again the RE integration leads to clean power production which helps to achieve the sustainable development goal 13. SDG 13 aims to combat the climate change and take the actions to restrict its impact. Thus this thesis can add some contributions to achieve these goals for the betterment of human living and the nature.

LIST OF ABBREVIATIONS

Abbreviations Used	Full Form
ABT	Availability Based Tariff
ACE	Area Control Error
AGC	Automatic Generation Control
GCE	Generation Control Error
UI	Unscheduled Interchange
SDG	Sustainable Development Goal
LFC	Load Frequency Control
PSO	Particle Swarm Optimization
FESS	Flywheel Energy Storage System
BESS	Battery Energy Storage System
PID	Proportion-Integral-Derivative
PD	Proportion-Derivative
PI	Proportion-Integral
DOF	Degree Of Freedom
EV	Electric Vehicle
CERC	Central Electricity Regulatory Commission
IT	Information Technology
ROE	Return On Equity
ANN	Artificial Neural Network
PSH	Pumped Storage Hydro
IBP	Integrated Business Planning
SMES	Superconducting Magnetic Energy Storage
AVC	Automatic Voltage Control
RES	Renewable Energy Source
ESS	Energy Storage System
DER	Distributed Energy Resources
DG	Distributed Generation
DEG	Diesel Engine Generator
HVDC	High Voltage Direct Current
HVAC	High Voltage Alternating Current
ISO	Independent System Operator
DSM	Deviation Settlement Management
EEX	European Energy Exchange
IEEE	Institute Of Electrical and Electronics Engineers
LMP	Locational Marginal Prices
GENCO	Generation Company
SEPIA	Simulator for Electric Power Industry Agent
EMCAS	Electricity Market Complex Adaptive System
DAM	Day Ahead Management
ECC	Energy Control Centre
NERC	North American Electric Reliability Corporation
WBPDCL	West Bengal Power Development Corporation Limited
PV	Photo Voltaic
SEF	System Frequency Elasticity

Abbreviations Used	**Full Form**
NR	Newton-Raphson
WTG	Wind Turbine Generator
FC	Fuel Cell
AE	Aqua Electrolyzer
UC	Ultracapacitor
MC	Marginal Cost
MW	Mega Watt
MWh	Mega Watt Hour

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Chapter 1: Introduction

The economic growth of any country majorly depends on its energy consumption. Till date fossil fuels are heavily used to generate energy in the usable form. It has led towards the environmental pollution, global warming and end of the fossil fuel storage. So, governmental and non-governmental organizations of different countries have taken the policies to reduce the use of fossil fuel and seek the renewable energy uses to meet the global energy demand. Hence the paradigm has shifted to harvest the energy in the usable form from solar, wind, biomass, biogas, geothermal etc in a sustainable manner. This attitude can save the fossil fuel and the globe from being grasped by the pollutants.

1.1 Introduction

One of the several usable forms of energy is the electricity. Researchers are working continuously to extract more power from solar, wind, pumped storage hydro plant etc renewable energy resources. Technological development and upgradation are being continuously done within and outside the laboratories to build efficient devises to transmit the power generated from the renewable energy resources to the grid. The integration of renewable energy to the grid is itself a challenge to the future power system. At the same time generation of clean and cheap power from the existing conventional power plants efficiently using better technologies are being focused worldwide. Co-combustion being one such economically viable technology is used for green clean energy generation [1]. Researchers are also prioritising to feed the power grid from hybrid generating units like thermal-hydro-wind or solar-wind-diesel/biomass or wind-pumped storage hydro plant etc [2, 3,4].

In this situation, to keep the grid frequency constant at a pre-set value, proper control schemes are needed to be implemented. In the existing automatic generation control (AGC) system, the same thing is done. The conventional generators like thermal, hydro, diesel generators implement speed governor based primary frequency control as well as Proportional-derivative-integration (PID) controller based secondary frequency control system to minimise the area control error (ACE). Two or more areas are interconnected through tie lines so that the fault in any generator can be compensated by the others from any area. In such situation the stability and the reliability of the grid operation is the most important in the power system operation as a whole.

In most of the countries the interconnected-power-system is operating. To supply power to the remote hilly regions or isolated islands, renewable energy based islanded power generations are getting importance. To get reliable power supply, not only a single power resource, but others renewable resources can also be integrated together and can form microgrids. In islanded scenario microgrids are quite fruitful and reliable. This invites the need of better electricity storage system, rather hybrid storage system comprising battery, ultracapacitor, flywheel etc [5,6]. In relation to it nowadays fuel cell technology and the hydrogen storage system are coming up. To power the electric vehicles (EV), such renewable based hybrid charging stations are being focused and built with the available technology. Grid-to-vehicle and vehicle-to-grid technologies are one of the mostly discussed and focused research areas these days.

The above discussion shows that the needs of hybrid power generation, integration of renewable energy resources with the conventional generation, the maintenance of the grid stability in terms of the grid frequency in an interconnected-power-system are highly important. Therefore the importance of automatic generation control cannot be neglected to maintain the grid discipline. Several works are done on AGC in the interconnected-power-system. One such research paper pioneering in this field showed how to control the battery energy storage system using area control error (ACE) in the load frequency control of interconnected reheat thermal system [7]. Several works on the load frequency control (LFC) have been explored in last two decades successfully [8,9,10,11,12,13].

The monopoly of the power business is interrupted worldwide with the introduction of restructuring of the power system. It has allowed the private participants to enter the power market through competition either in power generation or distribution initially. Therefore, monitoring and controlling the grid discipline in terms of the frequency in the interconnected-power-system became inevitable. In the next section role of the frequency control schemes are discussed in the restructured power system.

1.2 Restructuring of the Power System and Role of Frequency Control Schemes

As discussed in the earlier section, huge restructuring in the power system operation is welcome in different countries including India. This has changed the entire scenario of the power system operation. The vertically integrated electric power generation, transmission and distribution systems are disintegrated to horizontal components. At the same time private power producers and the distributors got the opportunities to step into the power business along with the government owned power plants and power distribution companies. So the generation and distribution of power entered the competitive power market, whereas the transmission system entered the competition later. The participations of several generators in one or more areas have introduced grid indiscipline which is detrimental for the power system operation. Hence the research works on automatic generation control (AGC) including the load frequency control (LFC) in the restructured power system has become necessary [14-18]. These include the renewable energy resources like PV based hybrid power generating systems also [19,20]. The controller optimizations are also embedded in these type of frequency control loop [21,22]. Hence load frequency control in the interconnected hybrid power systems with different optimization techniques are being studied for the purpose of stabilizing the power grid and frequency fluctuations even when the renewable resources like solar, wind are integrated via static converters.

The research works on the AGC show that the AGC schemes do not concentrate on the economy of the participants while carrying out the frequency control of the power grid. Now, consideration of the pricing due to the deviation of the actual generation from the scheduled one when the demand is perturbed also needs to be addressed. Hence deviations of the actual generation from the schedule generations are also take into account in the frequency control loop [23]. Basically earlier there are no incentives or penalties for the generators on generating more during the lean load period or generating less power during the peak demand period. Similarly for the power consumers there are no rule restricting more consumption during the peak load hours and consuming less during the low demand hours. To introduce such incentives or penalties to equalise the generation and demand imbalance in a power system some schemes are introduced with the government initiative. This scheme also needs to focus on the availability of the power from the scheduled generation. Hence the availability-based-tariff (ABT) concept has been conceived.

1.3 Availability-based-tariff (ABT)

In the Indian context, the restructuring of power is introduced through Indian Electricity Act 2003 to achieve the availability of power, the affordability and the grid discipline. To meet the objectives Central Electricity Regulatory Commission (CERC) has devised Availability-based-tariff (ABT) mechanism [23]. The central and the state regulatory commissions along with the state grid codes work together to implement the grid discipline. The state load dispatch centres take the responsibilities of implementing the intra state ABT schemes. Information Technology (IT) plays an important role to implement the data communication and to process data in the ABT regime. The scheme basically encourages the generators to generate more power during the peak load hours and reduce the generation during the lean load periods. Simultaneously, it discourages the power consumers to draw more power during the peak demand hours. This new tariff regulation induces discipline in the generation and the power consumption through proving some incentives and implementing penalties as and when required. The regulation is discussed in the next section.

1.3.1 ABT Regulation

The availability-based-tariff structure of the bilk power has three components. These are capacity charge, energy charge and the unscheduled interchange charge.

1.3.1.1 The Capacity Charge

It is directly connected with the declared capacity or the availability for 0-30% availability this fixed charge minus the ROE is payable. For 30%-70% availability prorated ROE is payable and beyond 70% incentives are paid. The incentive is fastened at 0.4% for availability within 70%-85% and thereafter the incentive drops to 0.3%. This strategy restricts the generators for over/under announcement of availability [23].

1.3.1.2 The Energy Charge

Second one is the energy charge. This one depends on the fuel expenses for the scheduled generation. In the two-part tariff the fixed and the variable charges are bundled together and paid in the share of the actual consumption by the consumers. In the three part tariff these two are separated. This new scheme promotes the power trading.

1.3.1.3 The Unscheduled Interchange (UI) Charge

The third one is the newest component of this three part tariff which depends on the deviation of the generation from the scheduled one. Penalty for deviating from the scheduled generation or drawl by an entity in the power system found necessary by the electricity regulatory body and the unscheduled interchange (UI) has been made payable in the situation when a generator output is not matched with the declared capacity, the frequency of the grid deviates i.e. it rises or falls. Similarly if the power consumers draw the power other than the scheduled consumption then also the grid frequency decreases or increases.

Now whether the penalty would be imposed or not that depends on the grid condition at that moment. If the grid indiscipline in terms of frequency deviation increases then the imposed penalty amount also increases. The ABT is implemented in phased manner. The 15 minute blocks i.e. 96 blocks in a day are being scheduled for generation and drawal. If the generators or the consumers fail to meet the schedule, then rescheduling is done through proper communication and coordination. Normally the regional dispatch centres manages and schedules the above scheme and takes care of the gird indiscipline. The ABT criterion also looks after the methodologies to be adopted by different types of plants to evaluate their competences, metering, payment etc. Some advantages like grid discipline, generation control etc. can be established through ABT which are discussed in the next section.

1.3.2 Advantages of Implementing ABT

The good quality and reliability of power can be made available if the grid discipline in terms of frequency is established in any interconnected-power-system. This can lead to better economic growth. ABT can make the participating power producers and the consumers self – disciplined through imposing incentives or penalties for over/under injection/drawal which leads to frequency fluctuation in the grid.

As the fixed and the variable costs are separated and the fixed charge is made proportional to the generator availability, the generators would try to maintain the efficiency good. In the ABT regime, the plant generates as much is needed. As the variable charge is proportional to the energy consumed, it would facilitate the power trading. Simultaneously, the fixed charge is proportional to the declared availability not the actual consumption. Hence the beneficiaries would trade in capacity. This indulges the competition and efficiency in the power industry. All these arrangements need sufficient infrastructure of the power transmission system which supports the ABT based self-regulated power market.

Thus the improved scheduling by the generators and the beneficiaries optimizes the available generation utilization. Simultaneously the area load dispatch centres can manage the load efficiently. Better metering system and online connectivity helps the system operators to get to know the actual power flow scenario and manage the power system operation. Transparency and faster system operation are also the benefits of the ABT. It also ensures improved communication and sharing of information between the participants. In overall the frequency stability is achieved, transmission loses are reduced and the transmission capacities are improved. Some difficulties associated with the implementation of ABT in the power system operation are addressed next.

1.3.3 Apprehensions about ABT

During the disruption of the grid which is beyond the grip of the generator or the beneficiaries, the scheduled and the unscheduled charges are difficult to fix. In such situation the regional load dispatch centres can resolve the issue, but the procedure needs careful handling. The declaration and the demonstration of the availability of the plants, calculation of the UI charges, rescheduling of the generators, consumption of the beneficiaries etc need more streamlined and transparent method.

The availability of the all kind of plants may not be predicted beforehand. Like wind farms availability can be predicted only for very short term. Hence the availability of renewable based generator whose input is nature depended cannot be scheduled beforehand.

There are also discriminations based on the age of the plant. The newer plants with latest technology differ a lot from the older plants in terms of the efficiency and the cost of the production. The regulatory commission relents to distinguish between the plants based on the above mentioned factor.

Finally the manipulation of availability, capacity scheduling by the participants to get undue advantages from UI charges can hamper ABT system. Hence proper checking and introducing effective clauses through severe penalties can limit such malpractices.

With the above mentioned benefits and the limitations of ABT system, it can be implemented effectively for the interconnected-power-system operation to mitigate the frequency fluctuation and establish the economic benefit of the generators/beneficiaries through grid discipline. So here comes the question of implementing the proper control schemes for maintaining the grid frequency at fixed value in the interconnected-power-system operation which is discussed next.

1.4 Availability-Based-Tariff in the Frequency Control Loop

Researchers have worked on the methodologies to fix the daily generation schedule of the declared capacity i.e. the availability through maximizing of the profit [24]. Proper mathematical model has been developed and a heuristic technique has been used to carry out the scheduling. The proper scheduling of the availability can minimize the unscheduled interchange (UI) in a power system and thus can reduce the frequency fluctuation of the grid.
For this purpose two area power system comprising thermal plants only have been studied [25]. A hybrid power generating system comprising a wind plant and a pumped storage hydro plant has been studied for unscheduled interchange (UI) between the scheduled generation and the actual one [26]. As the wind input is intermittent in nature, the scheduled generation is not possible to meet. Hence the unscheduled interchange between the grid and the hybrid system is violated. To overcome this problem, load scheduling technique has been adopted to maximize the profit through optimization. In [27,28] the application of ABT in the generation scheduling or scheduling the cost component of the transmission tariff using ANN have been studied. The frequency-linked-pricing has been also used to maximize the profit of a solar-wind-pumped storage hydro plant based hybrid system and thus to reduce the electricity cost. Besides optimizing the generation schedule of intermittent solar-wind power using the pumped storage hydro (PSH) plant, a work also utilizes the renewable resources demand side management. Moreover, it also maximizes the profit of the proposed hybrid system working

under Incentive Based Program (IBP) using frequency-linked-pricing [29]. Not only the renewable energy resources, the associated energy storage devices mean a lot in today's interconnected-power-system. Energy storage devices like Superconducting Magnetic Energy Storage system (SMES) or Supercapacitors can contribute in the voltage and frequency regulation in the deregulated interconnected-power-system [30]. A two area interconnected-power-system uses thermal power system, energy storage devices for the load frequency control (LFC) and automatic voltage control system (AVC). In LFC, the frequency-linked-pricing has been adopted for the thermal plant in the secondary control loop and the energy storage device has been kept under primary control loop. To improve the controller performance the integral controller has been used. Along with the conventional plants renewable energy based plants are also being incorporated nowadays for sustainable power generation (SDG 7) and this could be beneficiary for the betterment of the global climatic condition (SDG13). The next part of this chapter highlights on renewable integration along with the application of energy storage system in the hybrid power system.

1.5 Renewable integration and Incorporation of Energy Storage System in the Hybrid Power System

From the above discussions it can be said that the interconnected power grid is operational worldwide. Multiple generating stations run by different energy resources can deliver power at a fixed voltage level and can maintain the reliability of power system operation using proper control mechanism. Along with the non-renewable energy resources, RES also play important role in the integrated power system. Wind is one such renewable energy which is the widely acceptable and extensively used. The challenge like the cost of harvesting power from it is high. The involvement of energy for the machineries required for wind power generation and maintenance is huge. Again the intermittent nature of wind speed incorporates the uncertainty in the availability of power from it. Therefore, wind power better works with the other renewable/non-renewable sources like Solar, pumped storage hydro plant, fuel cell, diesel-biomass etc in the hybrid manner. Along with this energy resources flywheel energy storage, battery, ultra-capacitors etc can be utilised. Expansion of energy storage system (ESS) [31] for microgrids and isolated grid systems, bulk power producers, distribution network has been worked for the purpose of cost minimization. Hence the role of

RES and the ESS in the interconnected system cannot be overlooked. So the next focus is on the microgrid incorporation in the power system operation.

1.5.1 Microgrids in the Power System Operation

The microgrids are formed basically with distributed energy resources (DER) and interconnected loads which function together as a single controllable unit. It can generate, distribute and control the electricity supply to its local consumers [31]. It can operate in isolated manner or in the grid connected mode. It offers trustworthy local distribution network, upgraded power quality through load management, reduced carbon release, lower transmission and distribution losses etc [31]. Its indigenous distributed generation (DG) can avoid the grid congestion and lower the price of power. This in turn can benefit the local electricity consumers from paying high price of electricity during grid congestion and ensure better economic dispatch of energy for the utility grid. Microgrids along with RE based DGs and energy storage systems are discussed next.

1.5.2 Microgrids with Renewable Energy Resources (RES) and Energy Storage Systems (ESS)

Whenever the question of integrating the renewable energy resources in the grid appears, the stochastic nature of them comes into the picture. The wind and solar power cannot act alone or together as their availability is uncertain. Hence these energy resources can supply power along with the fuel cell in hybrid mode. The fuel cell can supply power in much reliable way. Fuel cell provides energy in the form of both electricity and heat to its customers [4]. Other than fuel cell, diesel generators (DEG) are also reliable for backup power supply. Considering the green power generation and reduced emission, instead of using diesel only, diesel and biomass can be used in 30/70 manner. In such hybrid system if the flywheel energy storage systems (FESS) and battery energy storage systems (BESS) are added then the system response becomes faster with the help of their high energy density [32]. FESS has the higher efficiency and longer lifespan than battery storage, whereas, the BESS provides the peak demand, though its efficiency and life span is poor [33]. The ultracapacitor can overcome the limitation of the BESS. It offers quick charge/discharge characteristic, improved efficiency and better power density. So, it can be operated in hybrid mode with the BESS and the FESS. Pumped hydro storage (PHS) plants can also play important role in the hybrid power generating system to mitigate the intermittent nature of wind and solar and sustain the supply-demand balance [34-35]. The offshore wind farms are capable to transmit bulk power through the HVDC or HVAC link. The HVDC links are the better option to transmit power beyond 50 km from the offshore wind farm with reduced loss compared to the HVAC links which are the better options for transmitting power to a distance within 50 km.

The observations gathered from the above discussion leads to a work on the application of the availability-based-tariff in an integrated hybrid interconnected-power-system to establish the frequency stability. The next section discusses the contribution of the thesis.

1.6 Contributions of the Thesis

This thesis has identified the problem of frequency fluctuation in an interconnected-power-system having multiple generators in multiple areas. The types of generators are also different. There are conventional generators like thermal generators which normally supply the base load. In addition to that hydro generators and the diesel/biomass generators are also incorporated in other areas. This scheme adds the power from renewable resources.

The governor based primary frequency control techniques are adopted for the above mentioned three generators. But the in the secondary frequency control loop unscheduled interchange based frequency control criterion has been adopted. As discussed in the earlier sections, that the availability-based-tariff (ABT) criterion has been adopted in the Governmental level to stabilise the grid frequency at 50 Hz in the Indian power system. Hence the deviation of actual generation from the scheduled on which is being declared by the generator a day ahead is used in the form of incentives or penalties to the generators/beneficiaries. This unscheduled interchange (UI) is converted into price following the frequency vs. Rs./MWHr. Curve imposed by the Central Electricity Regulatory Commission (CERC). Thus the UI price is used in the secondary control loop and the generation control error (GCE) is developed. This contains the information of frequency deviation as well as the deviation in the generation.

Using the above frequency control criterion, six different case studies have been done. Different situations which could have been arising in the interconnected-power-system have been investigated. This thesis has focus on the Indian power sector and followed the availability-based-tariff (ABT) structure to solve the frequency fluctuation problem.

- The transient behaviour of the interconnected-power-system with thermal-hydro-diesel/biomass in terms of frequency and power generations of all the generators have been studied when the areas are subjected to the load perturbations.
- Not only the sudden load change in the three areas, but also the effects of disconnecting the hydro plant or the diesel/biomass generator on the grid frequency as well as on the generations have been studied.
- The numbers of areas have been increased to observe the same effect on the tie-line power flowing between the areas when a sudden load change occurs and the disruption in generation in the hydro or diesel/biomass generators is observed.
- The next case includes the wind power in the control scheme. As the whole world is leading towards the sustainable power generation, it is needed to incorporate the wind power in the interconnected system as the renewable generator.
- The advanced technology of DFIG based wind generation has been adopted here. As the wind generators deliver power to the grid through static converters, the kinetic energy stored in its rotating parts cannot be transferred to the grid directly. Hence emulating inertia is used here.
- Now, the wind input being intermittent in nature, its availability cannot be declared day ahead like thermal, hydro or diesel/biomass generators. So, this work has kept the wind generator out of the ABT loop.
- The primary frequency control has been adopted for the wind generator. Frequency regulation in a three area thermal, hydro, wind and diesel/biomass based interconnected-power-system has been studied when it is subjected to the load perturbations and different situation dealing with the no availability of wind or hydro etc.
- In all the above case studies, the settlement of the frequency and other characteristics require proper choice of the controller gains. PI controller has been used for this purpose.
- In the next study, the optimization of the PI controller gains has been done using Particle Swarm Optimization technique (PSO) in thermal-hydro-wind based two area

hybrid power system. The application PSO has reduced the settling time of all the transient characteristics and achieved better performance.

- Further the effect of the wind power penetration on the unscheduled interchange (UI) price in an interconnected-power-system has been observed in another case study. It is found that though the penetration of wind power makes the settling time poorer, but the UI price gets improved with more wind power concentration. In future, the controller could be designed with better optimization techniques to address the larger settling time with more wind power.
- Lastly, incorporation of the microgrid in the interconnected-power-system has been studied. In the present day power system scenario, microgrid is an important component. The renewable energy resources like wind, fuel cell along with aqua electrolyser and the diesel/biomass generator are used as the power generators and the flywheel energy storage (FESS), battery energy storage (BESS) are used as the energy storage devices in the microgrid. This microgrid has been used in this case in the grid connected mode. It has been used as one of the participating generators in one area of the three area interconnected system. The frequency fluctuations with or without the microgrid and the other generators have been observed here under ABT regime.

Considering the above cases identified in the thesis, the contribution of the work can be enumerated as below.

- In studying the frequency regulation in different interconnected-power-system incorporating renewable energy resources in the ABT regime and the effect of the unscheduled interchange (UI) price on the grid discipline with some disturbances in the demand.
- In analysing the system dynamic responses, different resource deficiency situations like lack of wind or water flow or biomass etc are considered i.e. real world problems related to RE integration in the power system are addressed.

To carry out these studies, the power system models have been created in the MATLAB/Simulink platform. The gains of the PI controllers have been settled using MATLAB’s inbuilt optimiser. In some cases PSO program has been written in the MATLAB script and it is fed to the Simulink model and again updated. All the Simulink models and the corresponding programming descriptions are elaborated in the problem formulation chapter. The chapters are organised as given in the next section.

1.7 Organization of the Thesis

The thesis has been organised in the following manner.

1.7.1 Chapter 1

The general introduction of the thesis has been depicted here. The connection of frequency regulation and ABT in the interconnected-power-system has been portrayed in this chapter. Overall idea of ABT, unscheduled interchange (UI) price, the incorporation renewable energy resources in the load frequency control structure and their effects on the frequency regulation have been showed in chapter 1. Finally the contribution of the thesis is described.

1.7.2 Chapter 2

Chapter 2 is the State of Art available to identify the problem of the thesis. This chapter clearly discusses review works on the frequency-linked-pricing in the restructured power system. The deviation settlement arrangements along with the congestion management are also reviewed here. Works on the ancillary services like frequency and non-frequency control systems are discussed in this chapter. Moreover, automatic generation control in the ABT regime, the corresponding hybrid power generating systems and their optimization are reviewed here elaborately. It also includes the microgrid operation. Finally the literature surveys on the incorporation of the renewable energy resources in the interconnected-power-system and their effects on the grid discipline have been studied here. The works on the availability-based-tariff (ABT) in Indian power sector are also reviewed. The research gap has been identified thereafter and the problem of the thesis has been identified.

1.7.3 Chapter 3

This chapter describes all the six case studies to be done in the thesis. The block diagram of each case, the components of the interconnected systems, their transfer functions are all described here.

1.7.4 Chapter 4

Chapter 4 is very important as it describes the research methodologies adopted to solve all the six different problems discussed in chapter 3. It includes the particle swarm optimization techniques as used for optimizing the controller gains and the methodology to connect the MATLAB script with the Simulink models. There are several iterations required to interchange the data between MATLAB program and the Simulink blocks. Hence this case requires more computational time than the other cases.

1.7.5 Chapter 5

Chapter 5 is itself the heart of the thesis as it discusses the results obtained from the simulation of the cases and analyse the results obtained. The works depicted in case 1, case 2, case 4 and case 5 are all published in different conference proceedings published from IEEE and Allied Publishers. Case 3 has been published in the Journal titled International Transactions on Electrical Energy Systems published by Wiley.

1.7.6 Chapter 6

This chapter finally draws the conclusions on the problems solved in this thesis and some future scopes of the studies are mentioned.

The next chapter elaborately discusses the literature review on the effects of the ABT criterion on the frequency regulation of a multi-area interconnected power system and identifies the research gaps. The chapter also focuses on the works done related to renewable energy integration with the grid and the microgrid interconnection.

Chapter 2: State of the Art in Frequency Regulation of Interconnected-Power-System under ABT Regime

2.1 Introduction

The evolution of power system scenario in last twenty years has a conspicuous effect on human civilization. Considering the global climate change and the importance of the sustainability of energy, more stresses are given on green power generation which is not possible without harnessing the renewable energy resources (RES) along with the conventional energy resources side by side. Seventeen (17) Sustainability Development Goals (SDGs) are adopted in 2015 at the United Nations' Summit for betterment of human living worldwide, to restrict climate change, to eradicate poverty etc. Among these goals SDG 7 talks about the sustainable power generation [36]. It emphasizes on making the modern energy affordable and reliable in a sustainable way for all. Along with this SDG 13 also needs the mention in this thesis. It gives importance on the actions to be taken to restrict the climate change. Otherwise the world is going to face incredible adverse effect on the human civilization. Keep these goals in mind, this thesis has emphasized on the interconnected-power-system incorporating renewable energy (RE) based generators along with the conventional under availability-based-tariff regime. For example, in the India power sector, the shares of power generation are from solar energy 16.6%, from wind 10.4%, from hydro energy 11.1%, from small hydro 1.2%, from biomass/co-generation 2.4% and from waste-to-energy 0.1% i.e. 41.8% of 421.902 GW total generation capacity [37]. Such large amount of RE integration needs proper frequency control mechanism to maintain the grid stability when there is demand-generation imbalance.

The frequency regulation is the check point for this work in an environment of availability-based-tariff (ABT) [23 which can finally control the power generation from different generators economically leading to the restricted use of fossil fuel and reduction of the cost of generation. The detail costs of generation of the plants installed in India are reported in the executive summary of the Central Electricity Authority of India (CEA) [38]. The ABT system works for the central and the intrastate conventional generators networked through the power grids in India. Not only the large power grids, micro grids with distributed energy resources (DER) and smart grids with all technological advancements are coming up rapidly in the Indian power scenario. This helps to combat the transmission losses, mitigate the imbalance between demand and the supply of electricity followed by the maintenance of grid discipline etc. Integration of renewable energy resources mostly invites the inclusion of power converters, which in turn reduces the inertia of the grid. Therefore proper inertia control mechanism can boost the grid inertia and grid stability can be restored even if the renewable energies are integrated.

Future of power industry has to follow the integration of power generated both from conventional and renewable resources through proper interconnection with the grid. The deregulation of power system has transformed the entire power system operation situation starting from generation through transmission and to distribution. In restructured power system, considerable numbers of private companies are participating in the power production and the distribution of power other than the government organizations. In the power transmission sector also the private participations have entered. These initiatives together are improving the power scenario worldwide along with India. With these huge numbers of government and private participants, the entire power system operation requires proper grid stability and security, regulation of frequency. In India the share of the installed generation capacity in the central sector is 24.0% and in the state sector is 25.1%. Beside this government owned power companies can generate power around 50.9% of total installed capacity of 421.902 MW [37, 39]. Participation of all these power producers and the consumers, the frequency fluctuation in the power grid is obvious when it is subjected to the generation-demand imbalance. The automatic generation control (AGC) is used to maintain the frequency stability controlling the generation as per the demand change. Quite a large numbers of the research works are already done for the load frequency control of the conventional generators along with the renewable generators [40-59]. Since most of the renewable generators are connected with the grid through the static converters, they don not contribute to the grid inertia. As the correction measure the inertia control loops are introduced in the primary control schemes. This measure introduces emulating inertia and improves the grid stability. The private sector participation in the power system operation has incorporated the contract driven market structure which is monitored by the Independent System Operator called ISO [38]. This environment has led to the restructuring of the power sector and different methodologies have been adopted for the frequency regulation to implement the grid discipline.

In deregulated environment the financial losses and profits of the power producers and buyers have been given importance along with the system stability and security. Therefore independent system operators have been created to look after the co-ordination between Gencos, Transcos, Discos and the end-users [38]. This include supervision on power flow, information flow and money flow between the entities of restructure power system both in wholesale market and retail market economy.

In the new deregulated power sector, the frequency regulation is done using the price of power imbalance. Different rules for frequency-linked-pricing in deregulated power market have adopted worldwide. In India, at the beginning of this century Availability-based-tariff [60] was introduced. It was first implemented in the Western Region Electricity Board in 2002 [23].

ABT encompasses three part tariff comprising capacity charge, energy charge and unscheduled interchange (UI) charge [23]. The UI based control confirms no excess generation during off peak hours. It also sustains full demand during peak hours. Hence power producers and the buyers profit from such UI-based-frequency-control schemes. The thermal power plants already works with the UI based control. The capacity charge is related to the availability of the energy resources. Therefore ABT suits appropriately with conventional power plant like thermal, large hydro power plants. But, for renewable generations the availability of energy varies with the change of weather. Therefore variability of generated power output from renewable resources deserves extensive control for grid reliability.

Hence technical and economic coordination of generated power from renewable and non-renewable resources by different power producers require continuous control and supervision through load frequency control. The primary and conventional secondary frequency control of AGC does not ensure economic power generation from buyers and producers point of view. To achieve the grid stability and the economic power generation simultaneously the ABT-based-frequency-control is a good choice. Instead of conventional secondary control, Unscheduled Interchange (UI) price based frequency control has been adopted. Such attempt takes care of the grid frequency and the tie line power fluctuations of an interconnected-power-system. Promotion of ABT changes the conventional tariff structure. Quadratic cost functions of the plants are common in this situation. But inclusion of renewable power generation from solar, wind or any other resource questions the stability of the grid operation. These sources are weather dependent. Hence the power output from them cannot be declared beforehand. Moreover the cost functions such generations are also not known precisely. Therefore UI based control of such cases need separate attention. Hence UI based control of interconnected hybrid power system having thermal, hydro, solar, wind, diesel/biomass power generation deserve thorough review particularly under deregulation.

2.2 Frequency-linked-pricing in deregulated electricity market

As many participants in the power production or distribution system are getting involved, the need for frequency control of the interconnected-power-system has become evitable when these are operating under deregulation.

2.2.1 Deregulation of the Electricity Market

Deregulation in electricity market can terminate the monopoly of the electricity suppliers and remove control on prices. It can improve the efficiency; make the power system operation economical for the electricity buyers and the suppliers. It facilitates the participation of the contending suppliers. Without the proper market conditions, the consumers in the electric industry can be badly affected. The open access given to the power system entities does not introduce competition in the electricity markets. It imposes great challenges in the electricity trading. The major changes have been incurred in demand and supply system, transmission expansion planning, electricity transaction and retail operation. The competition in the electricity market incorporates new participants in the interconnected-power-system which in turn gives rise to frequency perturbation. Therefore influence of such new components in the power market needs attention to maintain the grid discipline in terms of frequency based pricing. The roles of the generators or the power producers i.e. supply side, the transmission companies, the power consumers i.e. demand side in the competitive electricity market need to be reviewed for stable power system operation.

2.2.2 Supply Side in the Deregulated Power System for frequency based Pricing Management

The conventional generators like thermal, hydro, diesel generators along with the renewable generators are operating in the interconnected-power-system under deregulation. The capacities of the generators in some large plants are huge. But nowadays the plants are being distributed with smaller capacities based on the locally available resources which include the renewable energy resources. So there operation and control under deregulation need attentions.

2.2.2.1 Restructured System with DER

Entry of the new generators to the power market has been encouraged in deregulated environment. With improved transmission and better market power control, utility generations are dissociated into smaller parts so that the electricity supply side is strengthened.

Till date conventional power plants cater the base load of an interconnected-power-system. Even after deregulation, they act as an important utility of power sector. Nowadays, renewable generation contributes a lot in the supply side of an interconnected-power-system. Distributed wind, solar participations fulfil the residual demand. A study [61] says that the low marginal cost generators including the distributed renewable generation can reduce the electricity spot price and depress the wholesale price of the electricity which is known as the merit order price. It has been modelled and tested for an installation of 5 GW solar plant in the Australian National Electricity Market (NEM) could have reduce from 12% to 8.6% of the net value traded through electricity pool from 2009 to 2010.

Another study [62] says that the long term effect of the merit order price due to distributed renewable energy integration is trivial. Under perfect market competition, for constant cost of base load generators with or without RES the long term merit order effect is nil. If the market is monopolistic, the long term merit order effect becomes negative considering the RES supply as the “fringe supply” in addition to the base load generators. If the RES and the peak load displace the based load then the new operational equilibrium is achieved and the again the long term effect of the merit order become negative. Such work can help to develop the empirical model of the merit order for the long term effect.

Another work [63] on the integration of solar power in the Czech Republic shows that the effect of the merit order is not negative and increases the cost at the consumer end. But the 10% increase in electricity generation from the other renewable resources (like wind power) whose merit order effect is negative can reduce the overall cost by 2.5%. One of the causes of such result for the solar plant merit order effect is identified as the improper choice of the plant location. Machine learning is also used to model the merit order price under the generation from solar, wind along with the base load generators like nuclear and lignite plants. Generation ramps also contribute to the high price due to less flexibility of the base load plants [64].

The above works say that the distributed generation with renewable resources have become essential part of the sustainable generation of electricity. But their intermittent nature brings the uncertainty in the generation. So the research works focus on the impact of uncertainty from distributed renewable generation on the supply side [65]. Utility with greater renewable penetration experience higher average buying cost per unit of electricity which is the local impact of renewable integration uncertainty. This results in less cost savings. But other utilities participating in the same regional market face decrease in their average buying cost of per unit electricity. This reflects the global impact of renewable uncertainty but can be managed by proper planning of hybridization.

Nowadays hybrid system conventional generators of different types are supplying power in a hybrid manner as well as in co-ordination with renewable generators. In a work the distributed energy resources are portrayed as important components of generation along with the conventional generators to supply the local loads. Their power dynamics of the DER are different from the conventional generators as they do not have the rotational inertia. This invites the difficulty in the power system stability and the integration of the renewable based DERs. Hence a proper co-ordinated control can improve the power system frequency stability. Beside reviews, a new frequency control technique adopted for DERs in Great Britain power system and South-east Australian power system are applied in this work [66].

Not only the supply side control, the demand side control and management are nowadays used in achieving the grid stability. The demand side operation is equally important as the supply side is in the power system operation. So the next sub-section reviews the demand side operation in the ABT regime.

2.2.3 Demand Side in Deregulated Power System in the Frequency-based-Pricing Environment

Deregulation imposes variability in demand. Demand side management (DSM) is an effort to reduce the cost by encouraging the electricity consumers to manage their load efficiently. Few loads are shifted from peak hours to the off-peak hours so that economic incentives can be given to them. Decision System, Intelligent Systems, Dynamic Programming, Evolutionary Programming etc are used to design DSM. One such study [i] observes reduction in the transmission line congestion using DSM and keep balance between supply and demand of electricity [67]. The active response of customers to the change of electricity supply and price are needed to support the study.

Other than DSM, auction is another approach held both at wholesale market and retail market to mitigate supply-demand imbalance in deregulated environment. In Full Spot Pricing scheme customers place the bid on the spot market based on the price and demand. But in Partial Spot Market [68], utilities contract with generators for long duration regarding electricity supply on daily basis. When the demand is more, auction at spot market are sorted partially [69].

Another approach to match the demand with supply is market power mitigation which is the ability of the market participants [70] to raise the level of price above the competitive levels for a long time. It can be vertical, horizontal and cartel-like. In this method the market power depends on minimum generation, residual supply and network flow. In deregulated power system, market power mitigation should be nil.

Another work proposes an algorithm to maintain demand–supply equilibrium by allowing utilities to establish hourly demand through proper communication setup. The Potluck problem [67] with non-rational learning has mitigated the demand–variability through prediction of optimal demand. In deregulated environment scheduling algorithm has been proposed to encourage the customers to use electricity during lean periods.

In a recent study [71] on a residential demand side management system, the correspondence between the grid frequency, surplus power, renewable energy stake vs. CO_2 contents and the corresponding price in the European Energy Exchange (EEX) has been evaluated. Due to lack of flexibility and enough throttling capabilities of the lignite and nuclear power plant in this particular case study of German Grid, excess power is generated during the high wind and the solar power generation. With the increase in renewable generation the gird frequency is increased and the increased the grid frequency is used as an indicator for demand side management to lower the CO_2 emission and electricity price when dynamic consumption tariff is available

Hence the supply side and the demand side management have been studied in different literatures to achieve the frequency regulation when linked with the electricity prices. The role of transmission of electricity through governmental or private initiatives also has important significance in the restructured power system through transmission expansion.

2.2.4 Transmission Expansion in the Deregulated Power System

Transmission in the deregulated environment plays important role for the interconnected-power-system. Open access to the power producers and distributors without any proper market conditions and necessary guideline it could be catastrophic for the power consumers. Hence power regulatory bodies are formed and proper control and monitoring of power generation, transmission and distribution are established in every country that has gone through such deregulation of power system. In such deregulated environment the control on transmission system is different from that on the generation and distribution. For pricing and expansion arrangements regional profit-making regulated transmission companies are incorporated in deregulated environment.

2.2.4.1 Uncertainties in Power Transmission System

As the uncertainties of power system are incorporated, the objective of transmission expansion planning has been changed after deregulation. The investors desire to encourage and facilitate the competition among electricity market participants, to provide fair access to economical generation for all consumers, to minimize the risk of investment against all uncertainties through transmission expansion planning. Other than this cost minimization of the transmission network, reduction of network charge, reduction of environmental impact, increase in network reliability and value of the system are among the major concern for transmission expansion strategy in deregulated power system [72].

In turn, the uncertainties and vagueness introduced in deregulated environments invite uncertainty in capacity enhancement of transmission system and risk in cost recovery. Therefore the planning for transmission expansion is delayed due to reduced incentives for investing in expansion and lack of fair mechanism. Hence this situation demands congestion management in deregulated environment. Hedging is considered as a solution to reduce the risk of expansion. It measures the risk of expansion planning and identifies the state where most robust plans are unwelcome. Consequently the expansion strategies are planned [73-77].

The supply side, demand side and the transmission operation and control in the restructure power system are well addressed in the new era of power system operation. The frequency-linked-pricing can be used for the control of the grid discipline and some balance between the power producers and the suppliers are needed to be controlled.

2.2.5 Trade-off Arrangement under Frequency based Pricing Management

2.2.5.1 Trading between Producers and Suppliers in Competitive Energy Market

During the birth of restructured electricity market, the trading of electricity is prevailing between the power producers and the suppliers in the competitive market. The problem like accepting the liability of power losses arose. Neither generators nor consumers are ready to compensate for the losses incurred. Hence the Independent Power System Operators has to accept the liability which is not fair. An analytical work focused on the existing transmission loss pricing methods which is based on proportional sharing, novel pricing and proposal is tested using IEEE standard 14 bus systems [78].

A work has proposed a scheme for reducing electricity price by imposing penalty for system failure arose due to the Gencos and Transcos. The affected price components are identified and calculated for the purpose of analysis. Moreover, the penalty scheme proposed here incentivises the Gencos and the Transcos to improve their reliability of operation as well as provides a control mechanism for ISO to reduce price risk [79].

In the restructured power system Locational Marginal Prices (LMP) [72] are the cost of incremental outputs of the generators to supply one unit of energy at a node without increasing the flow of the congested line. This varies with line load ability, losses in the line, generator bids, load cost, management planning made by ISO etc. Therefore the focus on the LMP has been done in a work which has given emphasis on LMP and congestion-surplus in the line due to trading of electricity. A 8-bus system has been adopted for LMP based analysis at different nodes. It has indicated the market power flow due to congestion based on DC-optimal power flow model [80]. The electricity is now being generated by several generators in a competitive market and they sell it in the wholesale market. So the pricing control plays an important role in the competitive power market.

2.2.6 Wholesale Approach in the Competitive Power Market

The deregulation process has introduced a wholesale market where the competing generators are selling power to the retailers and in retail market the customers are choosing suppliers from contending retailers. Thus retail energy service companies buy power from the GENCOs and sell it to the customers directly under deregulated environment. For this purpose pool based and bilateral transaction based market models are normally used. Such models demonstrate how the action and reactions of the market participants in retail market evolves in the changing financial and regulatory environment through simulations. Some papers have simulated agent based bilateral transactions in retail electricity market using SEPIA (Simulator for Electric Power Industry Agent) and EMCAS (Electricity Market Complex Adaptive System). These are able to establish their own objectives and take decisions. They can also learn through observation based learning and exploration based learning in retail electricity market. If buyers and sellers in electricity market are equipped with such tools, then they can interact through multi-issue negotiation in real life [81]. When several power producers sell electricity in the wholesale market, the amount of grid indiscipline introduced needs reliability check and control.

2.3 Reliable Grid Operation in Deregulated Electricity Market

Electric grid system connected with long transmission and distribution lines bears huge inertia. In restructure power system, electric grid is continuously being loaded with renewable energy sources and as a result the inertia is decreasing. Therefore maintenance of supply – demand balance always has become necessary for the sake for grid frequency discipline. Balancing supply and demand in real time is must to do; otherwise loss of electricity and blackouts would result [67, 82]. In horizontally integrated electricity market, the utilities try to maximize their own profits. Hence Independent System Operators (ISO) [38] are made responsible for managing the grid operation, scheduling generations, maintaining physical parameters of the grid, guiding investments in transmission infrastructure, maintaining supply-demand balance[67]. Different studies have proposed different approaches to mitigate the supply-demand imbalance through inclusion of storage, demand side management [56,71], auctions, market power mitigation etc[81].

Hence it can be inferred that to achieve the reliability and stability of grid operation in deregulated environment imbalance of supply and demand has to be mitigated. The reliable and stable operation of grid is possible when the grid frequency fluctuations are diminished quickly. Since the scheduled generation are decided based on the past experience, deviation of actual generation from the scheduled one gives rise to frequency fluctuations. Hence deviation settlement management has become indispensable.

2.4 Deviation Settlement Mechanism (DSM)

In power system operation the imbalance between the generation and the demand can give rise to frequency fluctuation which is detrimental for the power system itself. Blackout is one such adverse effect. To maintain the grid frequency at the nominal value (50.0 Hz in India), the demand should be predicted correctly and the generators should be scheduled day ahead. With proper frequency control ancillary service the frequency deviation is mitigated. The deviation settlement mechanism (DSM) regulations have developed in different countries to reduce the supply-demand mismatch.

2.4.1 Managing the Generation-Demand Imbalance

In competitive electricity market, imbalance between scheduled generation and actual generation, scheduled drawal and actual drawal are to be handled in real time through deviation settlement mechanism. This incorporates imbalance price, which is often interpreted as penalty mechanism. Presently such imbalances are dynamic in nature and apprehend market reality. In India, the Deviation Settlement Management prices are linked to Day Ahead Management (DAM) for 6-months basis and this is working from 01st April, 2018 [83]. Thus the proper generation scheduling can settle the generation-demand imbalance.

2.4.1.1 Management of Power Imbalance in India

In last 15 years imbalance management is prevailing in India at inter-state level. The evolution of Unscheduled Interchange (UI) price from July 2002 till date made the imbalance handling in India easier. The deviations are settled as per the UI/DSM Rate Vector managed by CERC. Present operational frequency band is ranged from 49.90 Hz – 50.05 Hz with a step of 0.01 Hz. The volume of deviation from scheduled to the actual injection/drawal is restricted to 150 MW or 12% of the scheduled, whichever is lower [23]. Out of 96 time blocks (each of 15 mins duration), the deviations are allowed to reverse within 12 time blocks [83].

Other than imbalance handling congestion management, handling of ancillary services, dispatch and scheduling Management in transmission line are other significant concerns for proper grid operation of deregulated electricity market. So the next sub-section highlights the grid congestion management.

2.4.2 Management of Grid Congestions

When one or more transmission lines are filled beyond the capacity, then this phenomenon is known as congestion management. The plant on import side of the line has to increase production and the plant on export side of line has to decrease the generation when congestion occurs.

In deregulated electricity market, when there is congestion in transmission, utilities have to get power for their customers from the generators within the import area and the spot prices for energy is higher compared to that of the export area. The value of congested transmission price is the difference of the price in import area minus the price in export area. The congestion model integrates energy market with the allocation and the pricing of the scarce transmission. Frequency and non-frequency based ancillary services can improve the grid stability.

2.4.3 Ancillary Services for Frequency and Non-frequency based Operation and Control

Ancillary services [84] in the power system operation facilitate and support uninterrupted power flow by the electric grid to satisfy the demand. These services are required to deliver electricity to the customers at stable frequency and voltages. Frequency regulation and control are encompassed under frequency related ancillary services. But the spinning reserves, the reactive power control, the voltage control and congestion management are considered as the non-frequency related ancillary services. These services are very much required to maintain the grid stability and security. Frequency control services are required to bring back the frequency to the nominal value which is hampered due to difference of generation and demand. Frequency should not be out of the range otherwise grid discipline gets distressed. Hence the power generation through operating reserve or the spinning reserve are desired to deliver load to maintain the grid frequency on an emergency basis.

An operating reserve can quickly be dispatched to meet the sufficient energy requirement of the load. Spinning reserves are already available in the grid in the form of generators and can hurriedly increase their power generation to meet the rapid changes in demand. Spinning reserves are required because demand can vary on short timescales and rapid response is needed. There are other generators which can deliver power to meet demand. These kinds of reserves are not able to respond as rapidly as spinning reserves. Hence the operating and the spinning reserves discussed here promote the frequency regulation.

With the help of reactive power compensation, the voltage control and the congestion management, non-frequency ancillary services are achieved beyond the generation and the transmission in the power system operation for the maintenance of the grid stability. Scheduling and dispatch, loss compensation, load following, energy imbalances etc are also provided as the ancillary services. Conventionally, large generation units are provided with the ancillary services. With the penetration of renewable based intermittent energy resources in the power system operation and the development of smart grid technology, the ancillary services are also assigned to the distributed generation systems and the consumption units also [86]. Beside the ancillary services the supply side scheduling and the demand side management can improve supply-demand mismatch and in turn can improve the frequency fluctuations.

2.4.4 Generation Scheduling and Dispatch Management

To maintain the reliability of the electricity grid, it is necessary to coordinate the generation and transmission units by independent system operator (ISO) or the transmission system operator.

In deregulated environment the deviation settlement has become a major issue which relate to the grid discipline in interconnected-power-system. Out of several management techniques, frequency control plays an important role. Normally frequency regulation for thermal or hydro generator based systems is accomplished for multi area power system using primary and secondary load frequency control mechanism. If the frequency regulation is linked with the deviation settlement through penalty mechanism, then the grid operation becomes both economically and technically sound.

The most popular frequency regulation method works worldwide is the Automatic Generation control (AGC). Frequency base pricing can be incorporated in the secondary or the tertiary loop of any load frequency control method implementation for any conventional or conventional and renewable based hybrid power system.

2.5 Automatic Generation Control through Availability-based-tariff (ABT)

The generators which can declare their generation day ahead can fix their availability i.e. the declared generation for the next day. Normally the conventional generators can follow this rule. Hence the mismatch of the actual generation from the scheduled one can be easily detected. Based on their capacity, fuel requirement for the scheduled generation and the deviation of the actual generation rom the scheduled generation the capacity charge, energy charge and the unscheduled interchange prices can be calculated. This is the three part tariff structure of the availability based tariff (ABT) system prevailing in India. In this thesis the ABT has been applied for the grid frequency regulation in an interconnected-power-system comprising hybrid power generation including RE. So some works on the automatic generation control and load frequency control for inter connected power system are discussed in the next sub-section.

2.5.1 Automatic Generation Control (AGC) for Interconnected-power-system

Automatic generation control involves the frequency measurement and measurements of net deviations on inter-state tie line which are followed by re-dispatching generation or shedding load. The objective is to diminish the frequency deviation. AGC works through Load Frequency Control (LFC) by maintaining the system frequency and the scheduled tie line power flow. It also facilitates the economic dispatch and establishes the security control with the help of the contingency analysis.

Reliable and good quality power transfer should be maintained in an interconnected-power-system under deregulated environment through proper choice of automatic generation control components [46, 87]. Sudden change in load introduces frequency fluctuations and tie-line power exchange. Here comes the bilateral contract between participating areas for implementation of proper LFC. Optimal output feedback, linear feedback, Kalman estimator [40, 53, 88, 90-93] are such few control strategies adopted elsewhere to accomplish the same.

These days some soft computing techniques have achieved popularity over the classical control strategies in designing load frequency control. Several optimization techniques like Genetic algorithm, Particle Swarm Optimization, Bacterial Foraging are currently being applied for the automatic generation control in multi-area system under deregulation [11, 14-17]. Such optimization techniques are also used for automatic generation control of interconnected-power-system without deregulation [10, 11, 12, 94]. These techniques are used either to tune the different types of controllers or to set the parameters for power system stabilizers. These actions enable operators to improve the frequency deviation situation and restoration of the tie line power fluctuations quickly. The role of soft computing techniques is discussed elaborately next.

2.5.1.1 Automatic Generation Control (AGC) with Soft Computing based PI/PD/PID Controllers

For the purpose of the frequency regulation automatic generation control (AGC) plays important role in the power system operation. To facilitate the AGC operation in the electric network the role of the controller is unquestionable. Mostly proportional-integral (PI) or proportional-integral-derivative (PID) controllers are used in the frequency control loop. Currently different soft computing tune PI or PID gains are effectively used to mitigate the frequency fluctuations. Here the control is optimized through BFOA i.e. Bacteria Foraging Optimization Algorithm. Such a research work [12] has implemented fractional order fuzzy controlled proportional-integral-derivative controller (FOFPID) to study load frequency control in a two area power system for frequency stability.

Another such work [22] has used fuzzy logic based fractional order PI controller along with fractional order PD controller to solve the AGC problem in an isolated and multi area power system. Imperialist competitive algorithm (ICA) has been used to optimize the PI and PD controller gains, the order of the integrator and the order of the differentiator. The robustness of this controller is established by the sensitivity analysis of the proposed system. A similar work [10] using cascaded fuzzy based fractional order PI and PID controller is demonstrated for a single and three area power systems AGC operation.

An algorithm based on the Chaotic Optimization Approach (COA) has been applied to determine the parameters of proportional-integral-derivative (PID) controller to study the automatic frequency control of thermal-hydro-gas and PV integrated multi area power system [9]. This paper also investigated the robustness of the controller proposed here under unstable mode of the power system with negative damping.

Another article [95] has introduced a two degree of freedom PI and PID controller with filter embedded in it for the load frequency control. The controllers are arranged in cascade. It has incorporated thermal power system, hydropower system, gas power system. This system works under the deregulation environment. The emulating inertia has been used to improve the grid inertia. The distributed generation (DG) and an aggregated electrical vehicle model (EV) model have been used to handle any kind of breach of contract in the power system. So the frequency regulation under deregulated power system operation has been studied in several research works in 2.5.1.1.

2.5.1.2 Load Frequency Control of Interconnected-power-system under Deregulation

An Independent system operator (ISO) [13] regulates the participation contracts. Contract between the areas is monitored and violation of the contract affects the situations [81]. In another work a fractional order controller (FOC) with static synchronous series compensator (SSSC) based damping has been used to study the frequency dynamics for a diverse GENCOs and multi-DISCOs integrated power system. The random load change and the un-contracted steps like contract violations are examined [15].

Another deregulated AGC model with PV-wind-diesel engine generator-aqua electrolyser-fuel cell based distributed generation (DG) incorporating the HVDC tie-line has been investigated for the frequency stability [11]. Here, emulating inertia control has been used with the energy storage system of the HVDC link. The Volleyball Premier League (VPL) algorithm has optimised the two-degree-freedom-PI and fractional order PD controller with filter is applied for the controller action.

Similar work with fuzzy PID controller and conventional PID controller with modified sine cosine algorithm (MSCA) has dealt with AGC problem under deregulation [17]. Application of Fruit Fly algorithm for automatic generation control of interconnected-power-system in deregulated environment is investigated with unified power flow controller (UPFC) and AC-DC link [18]. A very recent work has applied Moth Flame optimization (MFO) for optimization of the cascaded two degree of freedom PID-fractional order PD controller with filter and solved the two area AGC in deregulated power system [21].

These research works show that the AGC performs the control action considering generator with scheduled generation, tie-line set point, nominal frequency, actual generation, and actual tie-line power flow, actual frequency as the inputs to the power system with or without deregulation. Each state load dispatch centre (SLDC) requires AGC in their Energy Control Centre (ECC). As the renewable penetration has increased to promote green power generation and sustainable power generation, the role of AGC is getting more and more significance for grid regulation. Besides today's power generation scenario essentially embraces several renewable energy sources (RES) like solar, wind, small hydro, biomass etc between the areas. Hence reviews of some research works on frequency control of the RE integrated system are essential.

2.5.1.3 Load Frequency Control of RE Integrated Interconnected-power-system

The integration of the renewable energy (RE) in the power generating system has become an obvious choice. The control of such RE based power system needs more control action as they do not support the grid inertia or the availability of the power output for being stochastic in nature. In one such RE integrated power system the frequency regulation based on the demand response (DR) has been done with cascaded fractional order two degree freedom PI and PID controller with filter. A Quassi-oppositional-Harris-Hawks-optimization technique has been used for the controller parameter optimization purpose [96].

A recent work has applied Emotional-Brain-Learning-Based Controller for the load frequency control of two area power system with the solar-biomass integrated DG and energy storage devices. A unique use of EV is done to cater the intermittency of the PV input [20].

All the above discussions are focusing the frequency regulation of the interconnected-power-system with or without deregulation. The recent works include the renewable energy integration with the power system. But, these works do not embrace the unscheduled interchange based pricing which could control the excess generation or elevate the power production depending on the generation-demand imbalance. Hence the unscheduled interchange (UI) mechanism and the deviation settlement mechanism are used for load /generation interchange mechanism. Instead of market location prices, UI/DSM rates are used to regulate generation for change in load. Few research works are done on price based frequency regulation incorporating UI price in load frequency control loop. Before discussing it, Day Ahead Market (DAM) strategy needs the attention.

2.5.2 Real Time Power Grid Operation using Day Ahead Market (DAM) Strategy

Day-ahead market (DAM) influences power system participants' responses on real time grid operation. In 15 min DAM structure, the utilities take decisions to sell or purchase power based on the forecasts of the real time conditions for the same 15 min block of the next day. The real time injection/drawal into the grid fixes the amount of deviation from the schedule one which is set on the basis of organized market.

In India, the real time prices are DSM charges which are regulated and changes with frequency. DSM prices are kept lower than DAM prices considering that these are regulated and may lead to allocative and technical inefficiency. Hence DSM is used as a commercial mechanism to mitigate imbalance of generation and demand in the secondary control loop of AGC.

2.5.3 AGC under Price Based Operation

Some of the research works reveal the integration of price base operation in AGC. A set of two papers addressed the strategy for implementing the automatic generation control under price based operation at the onset of new electricity market structure. Bilateral based contracts, poolco based contracts and area regulation contracts are the pioneer of the market based transactions to smooth out the frequency oscillation caused due to unscheduled generation and load changes. A three area New England 30-bus test system is simulated for different transaction systems. The need of the area regulation in terms of the penalty cost is observed as a result of the contract violation. All the performances thus obtained conform to the FERC criterion [97, 98].

Pertaining to Indian power system, a huge restructuring is in need for better system operation and grid discipline through commercial incentives and dis-incentives. In consultation with international agencies India Government recommended a suitable tariff structure along with the introduction of Availability-based-tariff (ABT) for bulk power. Earlier regional grid used to function in a very undisciplined and jumbled manner. When the consumer load is more than the total generation at the grid, the frequency is lowered and the situation is managed either through reducing the load or by increasing the generation. High frequency is resulted during the off-peak period. No incentives are provided for reducing the load/enhancing the generation during peak hours or reducing the generation during off-peak hours. Generators used to earn profit by generating more power even during the lean period. Hence the grid indiscipline is prevailing in the earlier Indian tariff structure [99].

An earlier work [100] has focused on the system mean block frequency modelling and forecasting in respect to the frequency-linked-pricing mechanism. Earlier the participants of Indian power market are enabled to choose between long term contracts, short term bilateral contracts through pool through decentralised scheduling, self-dispatch, minimal communication with lower cost. Considering that a work on the unscheduled interchange established through automatic generation control does not involve much computational complexities. Similarly the self-dispatching ability has made the communication much simpler through the usages of local frequency meters. The decision on the change in generation is influenced by the comparison of the UI based Pool price and the generator's variable cost. Thus the self-healing of the plant and the grid frequency control is ensured. This operation involves the forecasting of the prospective values of the system mean frequency on hourly or daily basis.

Apart from conventional statistical forecasting techniques viz. regression, pattern recognition, time series, Kalman filter, some modern forecasting techniques like Artificial Neural Network (ANN), Fuzzy Logic, and wavelets are also used for ABT based block frequency prediction. One such work [101] has chosen ANN for its ability to model data rich system and identify the non-linear complex interdependencies within the data. This has led towards the application of the ANN for block frequency forecasting. The target of a gas turbine based plant is to minimize the difference between the energy cost and the UI charge with the help of predicted day ahead values of system mean block frequency. It is indeed the prerequisite for declaration of the plant's predicted availability for the next day. An ANN based MATLAB program predicts the system mean block frequencies which is to be utilized for decision making by generators, system operators and distributors.

Another work on frequency prediction using ANN solves generation scheduling problem through minimising the overall cost of the state utility [28]. Under or over predicted frequency range leads to the commitment for generating excess power or buying excess power from central generator at an elevated price. Hence an accurate frequency prediction facilitates proper optimization of generation schedule. This work predicts frequency a day ahead using feed forward error back propagation network. When a state beneficiary draws more power from central generators than pre-scheduled, it pays at higher rate for this unscheduled interchange under availability-based-tariff (ABT) regime. In contrary if it draws more power during lean load situation, it has to pay less. Thus grid discipline and security are ensured.

Several works are done to minimise the real power imbalance using availability-based-tariff. One of them proposes a mathematical model for daily scheduling of generator which maximised the profit with the application of ABT. The entire work is done on the basis of a forecasted frequency outline. Heuristic rules maximises the recovery of capital cost and the incentive earning from the frequency linked imbalanced power [24]. At first the capacity charge which is payable to the generating station and is calculated based on the monthly plant availability factor as defined by CERC is reviewed. It is followed by the calculation of the running charge which is the second part of the tariff. The calculation of energy charge payable to the plant is used for the average daily scheduling. Lastly the unscheduled interchange cost is evaluated following the UI rate. A comparison of % of time during which frequency remained within or around 50 Hz before and after implementation of the ABT reveals the improved frequency profile of North-Eastern and Eastern region of India [37].

The expressions of capacity charge, running charge and UI charge are modified for day ahead scheduling. The profit earned is then evaluated from the imbalance of power and it is optimised for maximum and net power generation. This formulation is applied for Santaldih Thermal Power Station (STPS) a unit under WBPDCL, India. Profit is calculated both for ABT based tariff and two part tariff and the result shows more profit earned per day for calculation with ABT based tariff and indicates the improvement of grid frequency as an outcome [24].

Automatic generation control (AGC) being an integral part of power system is associated with frequency based pricing and grid discipline by several researchers. One such work deals with the two area interconnected-power-system comprising thermal generators owned by different generation agencies. The generators are implemented with either conventional AGC or ABT based automatic generation control. The role of ABT is to accomplish switching operation between automatic generation control and non-automatic generation control. The generators with primary control only ramps down generation following the speed governing mechanism and losses the opportunity to avail the UI profit. The generators with secondary frequency control participate in uncontracted generation at higher marginal price which is not financially worthwhile. Generators with ABT based secondary frequency control facility without additional generation capability are not to earn profit due to unscheduled exchange. Finally the generators with ABT based control opportunity and additional generation capability earns profit due to unscheduled generation and restores the grid frequency quickly. Hence the revenue earned is maximised and the grid discipline is established [13].

The reviewed works involve mostly the conventional thermal generators. But in practice such systems are now to be extended for hybrid power generations involving renewable resources. Hence distributed energy resources (DER) are incorporated in hybrid power generations, even in the microgrids where frequency-linked-pricing is adopted. So the microgrid comprising DGs are very much essential for the localised power supply or in a grid connected mode. The grid frequency control of an interconnected system with microgrids or the frequency control of the microgrid itself is very important aspect of today’s power system operation. Hence the works on the price linked operation of the microgrids are discussed below.

2.6 Microgrids under Price Based Operation

Microgrids are single controllable unit which can generate power from distributed energy resources (DER) and can distribute it to its local consumers. It may operate in the grid connected mode. Some important features of its operation are reliable local distribution network, reduced transmission loss, improved load management, renewable energy incorporation, better power quality etc. Microgrids are also adopting frequency based pricing for a day ahead scheduling.

In a paper, authors have concentrated on two stage strategy. Wind, photovoltaic and pump storage hydro plant have been adopted as hybrid power generating system connected with grid. Hourly contract of delivery of power from the hybrid generating system to the microgrid is optimised first. Next is the consideration of the stochastic behaviour of the renewable resources where profit is maximised under frequency based pricing us in ABT regime. The optimum operating schedule of PSH in coordination of PV and Wind is determined to minimise the unscheduled interchange. A stochastic optimization problem is formulated to predict the uncertainties of wind and solar power generation and the market prices. When there is surplus power or the market price is low, the PHS pumped the water and delivered the power to the hybrid system. When the generation is less than the demand or the electricity price is higher, the PHS injected power to the grid and thus the system frequency is improved. Thus the work utilised a scenario based strategy to convert the stochastic problem to deterministic problem and ultimately the grid discipline is restored [102].

Distributed energy resources (DERs) are the heart of the new generation sustainable power system. DER involves renewable generators, hybrid storage system, distributed load to ensure reduced greenhouse gas emission and efficient operation of power system. DER being a major component of a microgrid influences the restructured electricity market worldwide. Operational protocols and market rules are continuously being upgraded to suit microgrids in future power system. When a microgrid comprising several DERs operates autonomously or on main grid, reliability of power supply and frequency regulation becomes a major challenge. Conventional frequency droop response of synchronous generators with large inertia is needed to be designed for power inverter based system implemented to incorporate DERs with grid in the restructured power market. One such work incorporated price based control framework in microgrid frequency regulation and real power balance [103]. Both supply and demand side DER are assimilated for regional energy market and also in ancillary services. The traditional frequency droop i.e. percentage change in frequency with respect to the percentage change in power generation has been associated with price droop. This has been defined as the percentage change in price due to one percent change in real power (load/generation). The proposed price based signal enabled DER to operate economically and governed the influence of each DER to droop response in the microgrid. The price droop values are evaluated for each DER for a given dispatch through multi agent learning process and updated in control loop by microgrid coordinator. The system disturbances are communicated in the form of price signals to each DER. The microgrid coordinator and the centralized system operator maintained the reliability and the stability of the microgrid and communicate with the distribution network. The public information like power system parameters are shared among DERs but the price droop values being the proprietary data are kept confined within a DER. The system frequency elasticity (SFE) as described by the percentage change in system frequency for a specified percentage change in system price remained same for all DERs in the microgrid. Microgrids involves the RE generation. Nowadays the hybrid power generating systems are using the RE generators as the fringe supply to improve the generation-demand mismatch. The works on such problems are discussed in the next section.

2.7 Renewable integration in hybrid power system under Availability-based-tariff to minimize the generation-demand imbalance and maximize the profit

The energy sources are classified as renewable and non-renewable energy considering their availability and renewal. The non-renewable energy resources cannot be replaced by the natural sources of energy. But the renewable energy resources can be replenished. Till date fossil fuels have been heavily utilized for the power generation. But their existence is now at stake. The depletion of such fossil fuels has forced the world to look for the renewable energy resources and the suitable technologies to harness electricity from these sources. For that purpose, solar, wind, hydro, biomass, geothermal, tidal powers etc are nowadays being used extensively for the generation of electricity. Large solar power plants or wind power plants are coming up. Besides these renewable energy sources are also being combined to form the hybrid power sources.

Since these sources are nature dependent, the availability of power is stochastic in nature. So, energy storage systems are also being combined with them to ensure the availability, reliability of power. Hybrid PV-wind power generation has been extensively focused for research and implemented for sustainable generation of power [29]. As there are continuous changes in the demand, variability in the wind speed, changes in solar insolation, a battery backup and the diesel generator are also used to ensure the availability of power output [9, 14]. A prefeasibility study on wind-fuel cell system is found better option than wind-solar-battery integrated standalone hybrid system [104]. To supply the local load diesel generators are used sometimes but it affects the environment adversely and it is not at all cost effective. The hybrid systems are better in terms of cost as well as in terms of environmental effect [105]. Micro-hydro power generation is another effective renewable power generation system [106]. In this work, a hilly area located remotely and not connected to main power grid has been supplied from a micro-hydro power generating system. But difficulty is with the availability of water throughout the year as this resource is nature dependent. Hence the intermittency of power from it is managed by diesel generator meet the local load. In hilly regions the diesel power generation is a popular choice which causes the environmental degradation. A hybridization of micro-hydro power generator and diesel generator is shown in that work as a suitable alternative to meet demand in such remote regions. Such eco-friendly and reliable combinations require low maintenance and can run effectively. Therefore the micro-hydro plants have come up as the one of the reliable resources in the hybrid power system. Thus solar, wind, micro hydro, biomass, fuels cell and the energy storage systems are gradually entering and changing the power generation scenario. But their penetration introduces frequency fluctuations in the grid which can be combated through proper LFC. Controlling the frequency fluctuation with the change in load is also associated with the control of generation so that the power system operation becomes economic. So the UI price linked frequency control is focused in several works in Indian power sector under ABT regime these days.

2.7.1 ABT in Indian Scenario to facilitate the Frequency Regulation

In India the implementation of renewable energy resources in deregulated scenario under availability-based-tariff regime has been experimenting continuously. One such research work has emphasised on the profit maximization of small hybrid power system based on wind power and a pumped storage hydro plant. This plant is connected to the grid. The pumped storage hydro plant operated to minimize the imbalance power and thus maximizing the profit [26]. Another ways to maximize the profit are through optimization of load management, RE integration etc [107]. Bee colony optimization [2] is adopted to get the optimal solution under frequency based pricing situation. The main load is supplied by the hybrid system as well as the grid and it is time varying and constant power load. Based on the forecasted wind power a contractual agreement is drawn between the hybrid system and the grid. The local load supplied by the hybrid system is modelled as the voltage dependent load. The load management is designed to control the demand response so that the demand could be met throughout the operating period. Several constraints like uncertainty in wind power generation, fluctuation in load, hydro power constraint etc influence the power flow from the hybrid system to the grid. Any deviation from the contracted power triggers to the imbalance in power. The Bee Colony based optimization technique has been used for the hybrid system to follow the prescheduled contract power. The surplus energy interchange is charged under the ABT rule. The pumped storage plant is utilised to add and shift load. Again it has compensated the deficit of power generated by wind energy in the hybrid system. Thus the shortfall and excess generation from wind generator has been managed through PSH unit and the profit is maximised using frequency based pricing.

In another similar work [26], it is accomplished through minimization of unscheduled interchange flow between the hybrid system and the grid. The hybrid system is supposed to cater its own load and deliver excess power to the grid according to a contract made between the two. But the stochastic nature of generated wind power gives rise to unscheduled interchange flow beyond the participants. To overcome this problem, load scheduling technique is adopted in the local load connected to the hybrid system. When the power delivered to the grid is less or equal to the contracted power, the actual power exchange is priced. But, when the power delivered to the grid is more than the contracted power, it is priced as per the contract. Newton-Raphson (NR) based load flow algorithm is used to model the load scheduling technique. The units supplied by the hybrid system and the unscheduled exchange for different wind profile are computed and compared. It is observed that the profit is earned with the implementation of proper load scheduling than the situation when the power is delivered to the grid without adopting appropriate load scheduling technique. Hence implementation of proper load scheduling technique could maximise the profit of the hybrid energy system.

In Indian power sector the cost of the unscheduled interchange (UI) of power flow is made frequency dependent [23]. Hence availability-based-tariff (ABT) has been introduced in India to establish grid discipline. The key to such mechanism is the frequency-linked-pricing. Several works on such frequency-based-pricing in interconnected-power-system have been reported in [13, 28, 29, 60, 108-112]. In these literatures influence of unscheduled interchange has been addressed through controller tuning and its effects on power flow between interconnected areas have been studied. ABT based optimal commitment and scheduling of generating units in an Indian state has been reported in [28].

Another work has proposed generation scheduling in an area considering predicted frequency and load variation using ANN under ABT regime [113]. A novel approach to maintain grid discipline has been proposed by some researchers. It utilises scheduled incremental and unscheduled interchange cost for day ahead and hourly scheduling in IEEE 14 bus system [27].

The ABT based frequency regulation can be applied for the thermal generators and hydro generators. Along with this, renewable energy sources (RES) like solar, wind, small hydro, biomass etc are needed to be incorporated in the power generation and control schemes for the sake of the sustainability. These are essentially nature depended and the irregular nature of the availability of these types of energy resources invites several challenges during their integration with the grid. To combat such stochastic nature of power generation from RE, Government has setup several regulatory frameworks on RES.

2.8 Sustainable Development Goals (SDGs)

All these reviewed works essentially focus on the frequency regulation in the ABT environment. The application areas are the interconnected-power-system with renewable energy resources and microgrids. This certainly leads to the sustainable power generation. The reduction in the frequency deviation is linked with the generation price of the generator. If it can be reduced the electricity can be made affordable to all. The two benefits are the essential goals of the sustainable development goals 7 (SDG 7). Such green generation of power can reduce the CO_2 emission with more RE integration in the power grid. This attempt can improve the global climate which is the sustainable development goal 13 (SDG 13). From the gaps identified below from the literature review done in this chapter, the SDG 7 and SDG 13 can be addressed.

There remain some gaps which can be addressed. This may be identified as the research gap between the applications of ABT based automatic generation control and the hybrid renewable based generation in interconnected-power-system. The incorporation of microgrid can also be studied for a future application of frequency regulation under ABT regime.

2.9 Research Gaps

The literature survey as portrayed in the preceding sections clearly indicates some research gap between the existing ABT based frequency control adaptation and the real world requirement. The future of power system is likely to evolve around complete renewable integration. Hence frequency regulation through ABT awaits the integration of renewable power generation as well as microgrids. Solar, wind, biomass, fuel cell based power generators along with battery-ultra-capacitor-pumped hydro storage based hybrid energy storage system together can form a microgrid and this can be considered as one of the entities of the interconnected hybrid power system.

- In this situation**, t**he frequency-linked-pricing can be applied for thermal, hydro and diesel/biomass generators.
- The constraint of having no proper allocation of the deviation charges for the renewable resources like wind/ solar /fuel cell limits the application of frequency-linked-pricing for the renewable resources.
- The availability of renewable resources is unpredictable. Therefore the electrical power output is unreliable for continuous operation. Hence its deviation from the scheduled generation and corresponding charge is not linked with frequency. UI rates of are yet to be developed for frequency deviation in renewable integration scenario. Therefore the studies related to frequency-linked-pricing in renewable based hybrid power system may be performed.
- The conventional generators can be treated under ABT environment whereas the wind and other renewable based resources may be exempted from the frequency-based-pricing control loop. Only primary frequency control can be considered for the renewable energy resources.
- The effect of the renewable energy penetration may also be studied under frequency based pricing environment.
- The effect of the renewable energy penetration on the unscheduled interchange (UI) price can be studied under ABT regime.
- The distributed generation (DG) has come up with new hope in interconnected-power-system. Microgrids being the combination of several renewable generations based on regional availability may be preferred by the customers of remote or

islanded locations. So microgrid can be incorporated in the interconnected-power-system.

- The DG based microgrids need to be connected with utility grid for more reliable power supply requirement. Hence the behaviour of an interconnected-power-system incorporated with microgrid in the availability-based-tariff situation is also needed to be explored.
- A multi area interconnected-power-system with microgrid integrated in one area can be studied under ABT based frequency regulation. The base loads of these areas may be supported through thermal generation. Conventional hydro generation and diesel/biomass generation may be incorporated in the interconnected system.
- The microgrid comprising offshore wind generator (WTG), fuel cell (FC), aqua electrolyser (AE), diesel generator (DEG), flywheel energy storage (FESS), ultra-capacitor (UC) and battery energy storage system (BESS) may be connected in one or two areas along with the conventional generators.
- Under ABT regime deviation of actual generation from the scheduled one is either penalised or incentivise to maintain the grid discipline. This UI based frequency control mechanism can be adopted in the proposed work.

The novelties of the work would be portrayed in investigating the influence of the microgrid, hybrid power generation, wind power etc on the grid frequency and the tie line power flow of the two/three/four area power system during unscheduled interchange. The MATLAB/Simulink may be used for the simulation purpose.

2.10 Novelties of the Work

By a thorough study of the frequency regulation of an interconnected-power-system under ABT regime the research gap has been identified. Based on that research gap, the working area of this thesis has been fixed. The novelties so ascertained out of those works have been listed below.

1. Unscheduled Interchange (UI) based price has been used for the secondary frequency control of thermal, hydro and diesel/biomass based hybrid two/three/four area interconnected-power-system.
2. The deviation of actual grid frequency from the nominal frequency which has occurred due to the generation-demand mismatch is considered along with the

deviation of the actual generation from the declared capacity for the calculation of the generation control error (GCE). The calculation of GCE for each thermal, hydro, diesel/biomass generator and the interconnection of two different generators like thermal-hydro, thermal-diesel/biomass, thermal-wind etc in multi area power system is a novel approach.

3. The application of unscheduled interchange based pricing for frequency regulation of such hybrid power generating system can be considered as one of the novelties of this work.
4. The study is done for the frequency fluctuation, tie-line power deviation and fluctuation in the generation when the hydro power or the diesel/biomass generations are stalled or any area is disconnected from the others due to certain natural calamity or disruption in the power system operation.
5. Understanding the importance of the RE integration, wind power generator has been incorporated in the interconnected-power-system in one area of the multi area power system. As its availability cannot be declared day ahead, it is kept out of the availability-based-tariff scheme. Only primary frequency control through emulating inertia has been used fir the wind power.
6. To get better system dynamic responses i.e. reduced peak overshoot/undershoot, improved settling time etc, the proportional-integral (PI) controller or proportional-integral-derivative (PID) controller gains are optimized through particle swarm optimization technique (PSO). Here the link between the MATLAB script where the PSO program is written and the block diagram of the interconnected-power-system model is another novelty of this work.
7. The unscheduled interchange (UI) rate (Rs./MWHr.) for the generators operating in the chosen interconnected-power-system are calculated which gives the idea of the profit or loss of the generators for unscheduled interchange of power.
8. The effect of the wind energy penetration in the interconnected-power-system has been investigated and its effects on the UI rate are also evaluated for different wind penetration scenario.
9. Lastly the incorporation of the microgrid in one area has been studied for the frequency regulation of the interconnected-power-system under ABT. The components of the microgrid are mostly renewable energy resource (RES) based

generators like wind, fuel cell, aqua electrolyser, diesel engine generator, flywheel energy storage system and battery energy storage system.

As the research gaps have been identified already, these research problems based on these gaps are formulated in the next chapter. In total six cases have been identified. Among these works first five cases are already published in journal and conference papers. The sixth case has been communicated in a journal paper and is under the review process. The third chapter enumerates the problem formulations of the identified works given inside the thesis.

Chapter3: Problem Formulations

To study the stability of an interconnected-power-system with respect to frequency and tie-line power we have formulated six different cases combing the conventional and the renewable power generators mostly in Indian context. In the previous chapter the detailed literature review has identifies some research gaps in the frequency regulation of multi-area interconnected-power-system under ABT regime. From there the case studies to be formulated in this chapter have been identified. The solution methodologies used to solve the problems are discussed in the Chapter 4. Here, we formulate six different problems related to the above mentioned situations.

3.1 Case1: Secondary-frequency-control of Three Area Thermal-Hydro-Diesel/Biomass Hybrid Power System based on Unscheduled Interchange (UI) Price

In this case, a three area interconnected-power-system has been adopted to study the frequency regulation under Availability-based-tariff (ABT) [109]. Area 1 is supplied from two thermal generating units whereas Area 2 has a single thermal and one hydro power generator. The third area has one thermal and one diesel generating unit. Figure 3.1 depicts the complete block diagram of the proposed interconnected-power-system embedded with unscheduled interchange (UI) based control blocks. In the primary-frequency-control loop, the Free Mode of Governor Operation (FMGO) is used. In this conventional primary-frequency-control system, the frequency deviates from their nominal values and the generator output changes from the scheduled value with the change of load. Automatic generation control brings the system frequency to the nominal value. The contribution of the unscheduled interchange (UI) based price blocks are newly added in the secondary level frequency control to implement the availability-based-tariff mechanism in the proposed frequency regulation technique. The marginal costs of generation of the generators are evaluated through a logical program written in MATLAB/Simulink function and an error signal is generated to establish the price based secondary-frequency-control. Following sub sections explain the mathematical

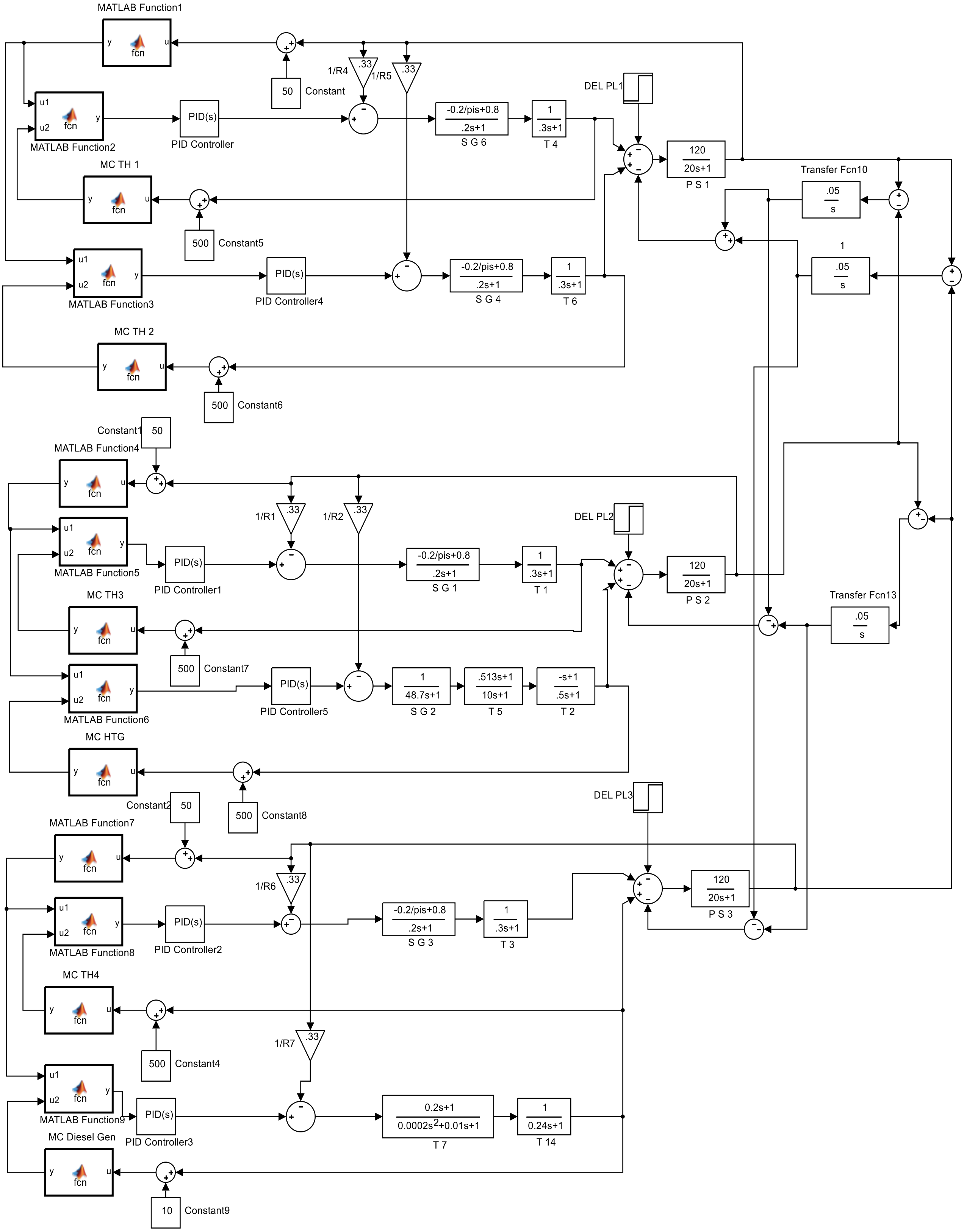

Figure 3.1 Simulink model of Unscheduled Interchange (UI) price based secondary-frequency-control of thermal-hydro-diesel hybrid three area power system [109].

formulation of the marginal cost of the thermal, hydro and the diesel generating units which are required to solve the frequency control problem under ABT criterion.

3.1.1 Calculation of the Marginal Cost (MC)

In ABT mechanism, three part tariff is followed. The capacity cost of generator is developed based on the availability of generator output. The second component known as the energy cost is the depended on the fuel usages as per the scheduled generation. In a thermal generating unit capacity charge and the energy charge are combined following the heat rate curve of thermal conversion system to formulate the marginal cost (MC_{th}). The expression the marginal cost is written in (1) for the proposed case [113,114].

$$MC_{th} = a_i + b_i P_{Gi} \, (Rs./MWh) \qquad (1)$$

Here a_i and b_i are the first and second order cost coefficients respectively and P_{Gi} is the power generated in MW in i^{th} thermal plant loop.

The marginal cost of a hydro power plant (MC_h) is expressed in (2). It is dependent on the flow of water [116].

$$MC_h = c_i + d_i P_{Gi} \, (Rs./MWh) \qquad (2)$$

Here c_i and d_i are first and second order cost coefficients respectively. The generated power is P_{Gi} in MW in i^{th} hydroelectric plant.

The amount of fuel burnt determines the marginal cost of a diesel generator (MC_d) [116]. It is expressed in equation (3).

$$MC_d = e_i + f_i P_{Gi} \, (Rs./MWh) \qquad (3)$$

The first and second order cost coefficients are e_i and f_i respectively and P_{Gi} is the generated power in MW in the i^{th} diesel generator. These marginal costs are used to evaluate the generation control error (GCE) along with the frequency deviation based UI charge.

3.1.2 Calculation of the Unscheduled Interchange (UI) charge

The third part in the ABT base tariff is the charge accounted for the Unscheduled Interchange (UI) of power. Unscheduled Interchange is the deviation of the actual generation from the scheduled generation, the price of which is regulated by the CERC Regulation, 2014. As per Table 3.1, unscheduled interchange charge is calculated based on the frequency of generation at that moment. The UI price is fixed at 178 Paise/kWh at 50.0 Hz [23] according to the CERC Regulation 2014. The UI price is 178 Paise/kWh when the generators the scheduled power at 50.0 Hz and the loads connected consumes power as per schedule at 50.0 Hz. To calculate the UI price Table 3.1is used and the MATLAB function blocks are embedded in the Simulink model of the proposed hybrid power system.

The marginal cost and the UI charge of each conventional generator are considered as the input to the secondary control loop of the ABT based scheme.

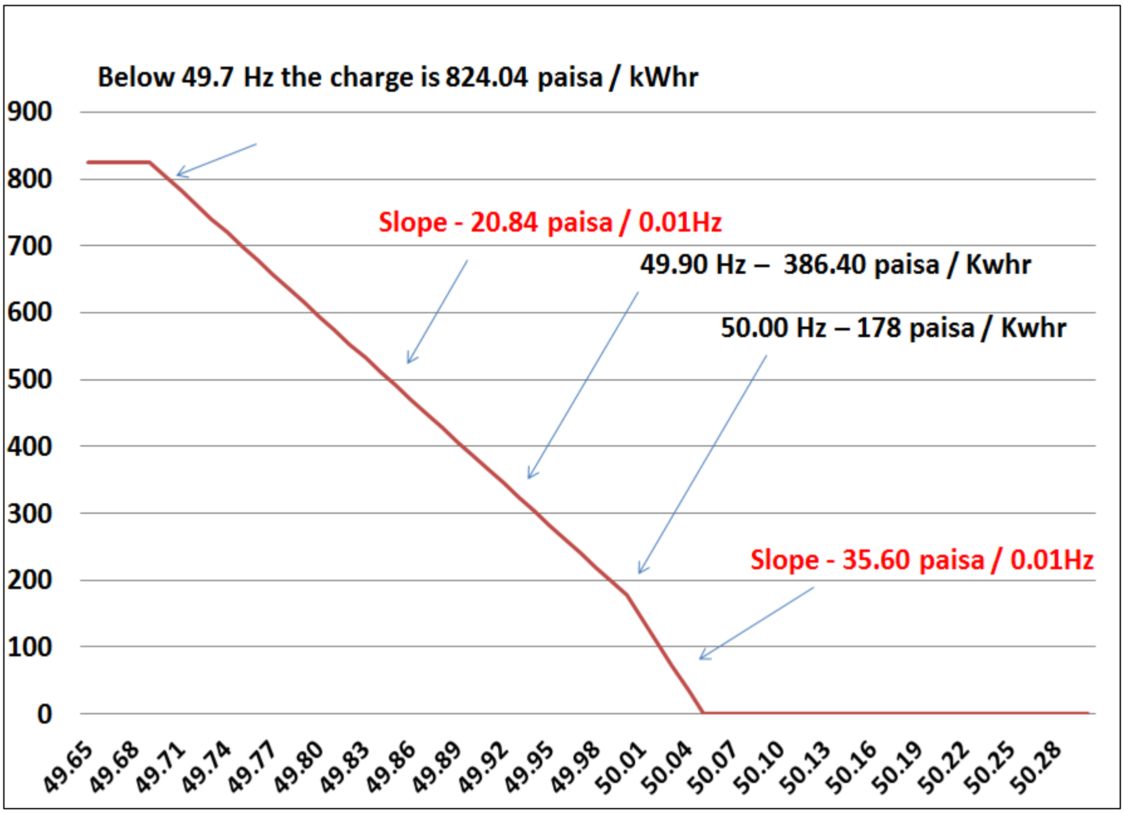

Figure 3.2 Unscheduled Interchange (UI) charge in paise/kWhr. Vs. frequency (HZ) characteristic as imposed by the CERC [23]

Table 3.1 Charges for Deviation settled by Central Electricity Regulatory Commission (Deviation Settlement Mechanism and related matters) Regulations, 2014 [23]

Average Frequency of the time block(Hz)		**Charges for Deviation**
Below	**Not Below**	**Paise/kWh**
50.05		0.00
50.05	50.04	35.60
50.04	50.03	71.20
50.03	50.02	106.80
50.02	50.01	142.40
50.01	50.00	178.00
50.00	49.99	198.84
49.99	49.98	219.68
49.98	49.97	240.52
49.97	49.96	261.36
49.96	49.95	282.20
49.95	49.94	303.04
49.94	49.93	323.88
49.93	49.92	344.72
49.92	49.91	365.56
49.91	49.90	386.40
49.90	49.89	407.24
49.89	49.88	428.08
49.88	49.87	448.92
49.87	49.86	469.76
49.86	49.85	490.60
49.85	49.84	511.44
49.84	49.83	532.28
49.83	49.82	553.12
49.82	49.81	573.96

49.81	49.80	594.80
49.80	49.79	615.64
49.79	49.78	636.48
49.78	49.77	657.32
49.77	49.76	678.16
49.76	49.75	699.00
49.75	49.74	719.84
49.74	49.73	740.68
49.73	49.72	761.52
49.72	49.71	782.36
49.71	49.70	803.20
49.70		824.04

3.1.3 Control Scheme Adopted for Frequency Regulation

The control scheme to regulate the frequency of the interconnected system has been developed as per the ABT mechanism. When the power plant delivers beyond its scheduled generation, then the energy charge is paid for the scheduled capacity and the excess generation is paid according to the unscheduled interchange charges. If the grid operates at that time with excess power at a frequency above 50.0 Hz, the UI rate is small. If the same situation arises during the generation deficit at a grid frequency below 50.0 Hz, the plant will get UI charge at higher rate. The reverse situation will occur when the generator will deliver less power to the grid. This price control logic under ABT scheme is established through another MATLAB code which considers the UI charges, marginal costs. This error signal generated from the MATLAB blocks is sent to the PID controller which in turn is tuned using internal tuning mechanism inbuilt in the MATLAB/Simulink.

Thus the secondary-frequency-control loop incorporates the Unscheduled Interchange based ABT mechanism for the frequency regulation of an interconnected-power-system. The next case extends its application incorporating more power system areas and observing effects of UI on the tie-line power flow fluctuations.

3.2 Case2: Application of UI Price based Secondary-frequency-control on a Four-Area Hybrid Power System and its Effects on Tie-line Power Flow

A four area interconnected-power-system (Figure 3.2) having thermal, hydro, and diesel/biomass power generation has been used in this case [110]. Till date, the potential of fossil fuel based power generation in India plays an important role. But the paradigm is shifting towards the renewable energy based power generations for upcoming era. Here, the thermal power plants are chosen as the major power producers followed by the hydel plant and the diesel/biomass power generation. Area1 consists of two thermal generators. Area 2 has one thermal and one hydro generator. Area 3 is supplied from a thermal generator as well as from a diesel/biomass generator. Area 4 has a combination of hydro-diesel/biomass generators. Table 3.3 shows the capacities of the generators connected in the proposed hybrid power generating system. The primary-frequency-control scheme of the conventional generators follow speed governor based control. But the secondary control adopts the unscheduled interchange (UI) based price control scheme. The secondary-frequency-control and the tie-line power control are described in the following sub-sections.

3.2.1 UI price based secondary-frequency-control

The third component of the ABT based three part tariff is unscheduled interchange (UI) charge. The charges for deviations from the scheduled generation in all the time blocks are considered in this case study in a similar manner that of the Case1. The calculated UI price (INR/MWh) in each time block is compared with the marginal cost which is calculated based on the input-output curve of the generating units. The cost (MC_{th} in $(Rs./MWh)$) curve of the thermal generators follows the heat rate curve and the equation is shown in (1) [115]. The marginal cost of the hydel power plant is calculated based on the water flow. This cost $MC_h(Rs./MWh)$) is expressed in (2) [116, 117].

The diesel generator starts with the diesel, but during the run condition it uses the biomass. Hence the utilization of renewable energy is accomplished. As the marginal cost of diesel/biomass generator depends on fuel burned, its cost $MC_d(Rs./MWh)$ is written as the function of generated power (P_{gi}) in MW in the i^{th} diesel/biomass generator (3). It has the first and second order cost coefficients e_i (Rs./MWh) and f_i (Rs./MWh^2) respectively [118].

Similar to the previous case, the marginal cost amounts the cost of energy used for actual power generation. The unscheduled interchange charges are calculated based on the UI rates and the corresponding generation control error (GCE) is calculated. A suitably tuned PID controller has been then used with each generator which controls the generation control error and facilitates the secondary-frequency-control.

In this case more numbers of the power system areas have been incorporated to study the effect of the tie-line connection/disconnection and other weather dependent situations.

3.2.2 Calculation of The Tie-line Power

In this case, the Tie-line power flows between the power system areas. The incremental power balance equation as a function of incremental changes in load angles can determine the tie-line power flow. The equation of the tie-line power of area 1 is shown in (4). Here T_{12}, T_{13} and T_{14} are the synchronizing power coefficients between area 1and area 2; area 1and area 3; area1 and area4 respectively. The changes in tie-line power of the areas are also evaluated for the sudden changes in load in all the four areas as expressed in equation (4).

$$\Delta P_{tie1}(s) = \frac{2\pi T_{12}}{s}[\Delta F_1(s) - \Delta F_2(s)] + \frac{2\pi T_{13}}{s}[\Delta F_1(s) - \Delta F_3(s)] + \frac{2\pi T_{14}}{s}[\Delta F_1(s) - \Delta F_4(s)] \quad (4)$$

In the secondary control loop, the generation control error (GCE) is calculated as discussed in the earlier sub-section. The tie-line power is also evaluated by taking its feedback and the generation control error is reiterated. Thus the new area control error (ACE) of j_{th} area is obtained as shown in equation (5) where GCE_i and ΔP_{tiej} are the generation control error of i_{th} generator and tie-line power deviation of j_{th} area respectively.

$$ACE_j = GCE_i + \Delta P_{tiej} \quad (5)$$

In the next case wind turbine generator (WTG) has been incorporated to study the effect of RE integration.

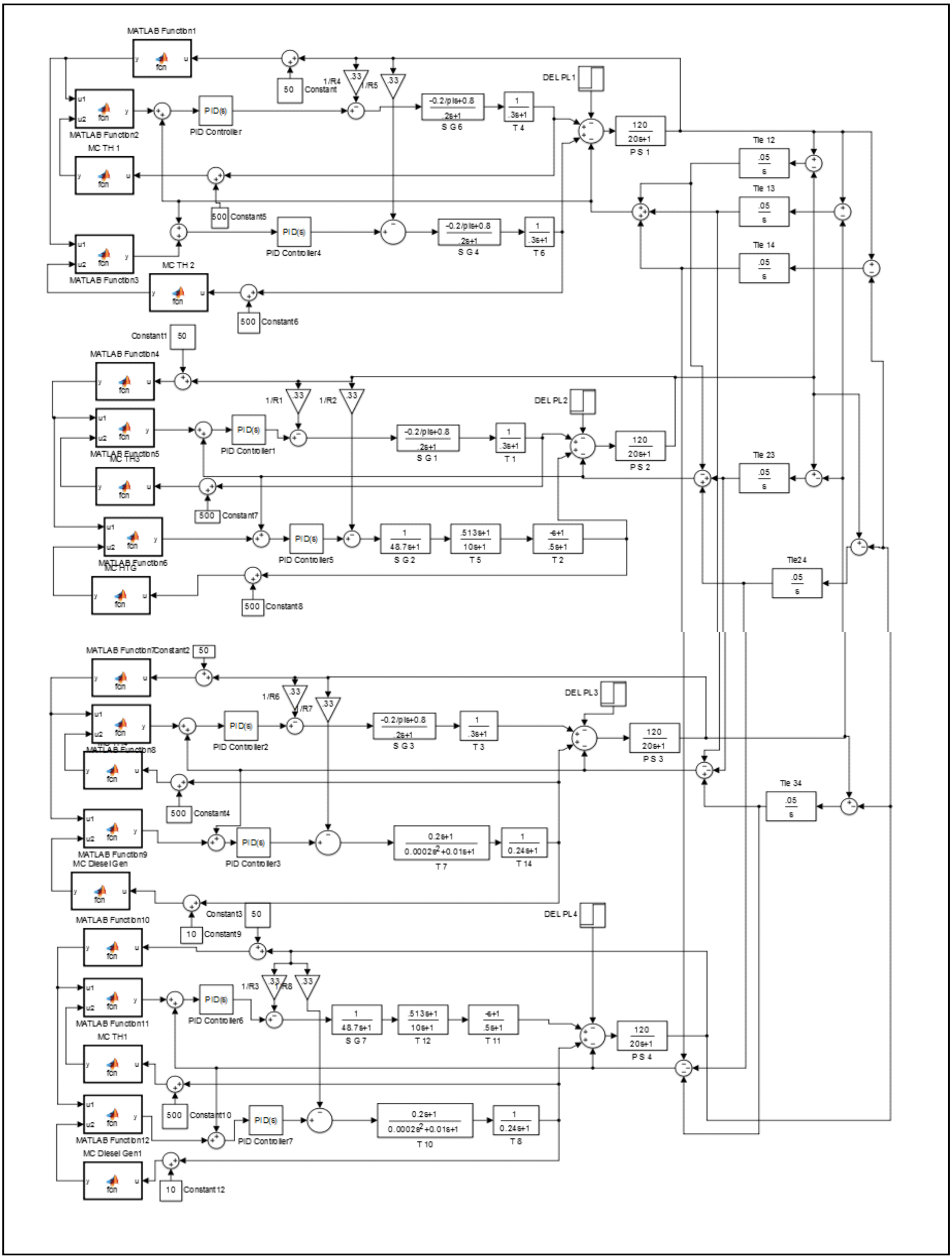

Figure 3.3 Block diagram of UI price based four area load frequency control [110]

3.3 Case3: Frequency Regulation of Thermal-Hydro-Diesel/biomass-Wind Power Integrated Indian Power System under Availability-based-tariff

Case 3 has incorporated a wind turbine generator in a thermal-hydro-diesel/biomass based interconnected three area power system under ABT rule [108]. Such attempt has been made to achieve the sustainable development goal 7 (SDG 7) in terms of reliability, affordability and sustainability of energy usage. The electricity thus generated should reach the people worldwide by 2030. In India the wind power can be harnessed for electricity generation in some suitable places which can be connected with the other conventional generators in an interconnected mode. There are few challenges to connect the wind turbine generator with the grid. Wind generators are normally connected through static converters with the grid. Hence the rotating inertia of the blades are not directly transfer to the grid. In contrary the other generators i.e. thermal, hydro and diesel/biomass generators use synchronous generator to get the electricity. These generators directly transfer their rotating inertia to the grid and as a consequence the grid stability is maintained. In the governor based primary-frequency-control and the ABT based secondary-frequency-control schemes of these conventional generators ensure the frequency regulation in an economic manner. This has been already shown in case 1 and case 2. This case takes the challenge of WTG interconnection through emulating inertia. This inertia helps to add to the grid inertia for the WTG.

Doubly Fed Induction Generator (DFIG) has been used as the wind power generators. The hidden inertia due to the huge kinetic energy stored in the wind turbine blades support the primary frequency regulation. This is described in the following sub-sections. The combined frequency control of the static converters and the pitch control of the WTG adjust the active power output and rotor speed. For this purpose the de-loaded optimum power extraction curve is the most useful criterion. The next section describes the transfer function models of the generators used in this case.

3.3.1 Transfer Function (TF) Model of the Thermal Generator

The speed governor TF, steam turbine TF and the synchronous generator TF together form the thermal generator transfer function model. The thermal generator transfer function has the cascade connection of the blocks of speed-governor system and a steam turbine system as represented by equation (6) and (7) [88]. They together form forward path of the primary-frequency-control loop. The speed governor dead band has been considered to be 0.05%. Equation (7) expresses the steam turbine transfer function. Here N_2 and N_1 are the governor dead band block constant and T_{SG} is the speed governor time constant. Here T_t is called the turbine time constant.

$$G_{SG}(S) = \frac{-N_2/\omega_0 s + N_1}{T_{SG}s + 1} \tag{6}$$

$$G_T(S) = \frac{1}{T_t s + 1} \tag{7}$$

3.3.2 Transfer Function Model Hydro Turbine Generator

A hydraulic turbine is influenced by the water inertia and compressibility, pipe wall elasticity of the penstock. The turbine power output changes with the change in gate position. As the rate feedback provides the temporary large transient droop with long resetting time, the gate movement is restricted until the water flow and the power output are synchronized. The gate position is controlled through the primary speed–load control system. Therefore the hydro-turbine speed governing system establishes the droop compensation and stabilizes the water inertia. The speed governor is linked with hydraulic amplifier which controls the hydro turbine output. The transfer functions of speed governor, hydraulic amplifier and the hydro turbine are depicted in (8), (9) and (10) [119] where the transfer function of hydraulic speed governor is T_{SGH}. The corresponding gain is K_{SGH} and the reset time is T_r. The hydraulic amplifier time constant is T_{HA} and the water starting time is T_w. The time required for the water head in the penstock to accelerate from zero to steady discharge is known as the water starting time.

$$G_{SGH}(S) = \frac{K_{SGH}}{1 + sT_{SGH}} \tag{8}$$

$$G_{HA}(S) = \frac{1 + sT_r}{1 + ST_{HA}} \tag{9}$$

$$G_{HT}(S) = \frac{1 - sT_w}{1 + s0.5sT_w} \qquad (10)$$

3.3.3 Transfer Function Model Wind Turbine Generator

As discussed in the beginning of this case study, the wind turbine generators normally do not participate in the load frequency control. If the variable speed generators like DFIGs are used to extract power from the wind turbines, then the stored kinetic energy in the rotor can be utilized. The power generated from the generator is delivered to the grid. The stored kinetic energy of the mechanical system of the wind turbine does not directly contribute to the grid. Therefore the hidden inertia of the wind energy conversion system contributes through the emulating inertia. The modelling of the DFIG based primary-frequency-control system is shown in Figure 3.3. The block diagram of the primary-frequency-control block diagram is developed as discussed below.

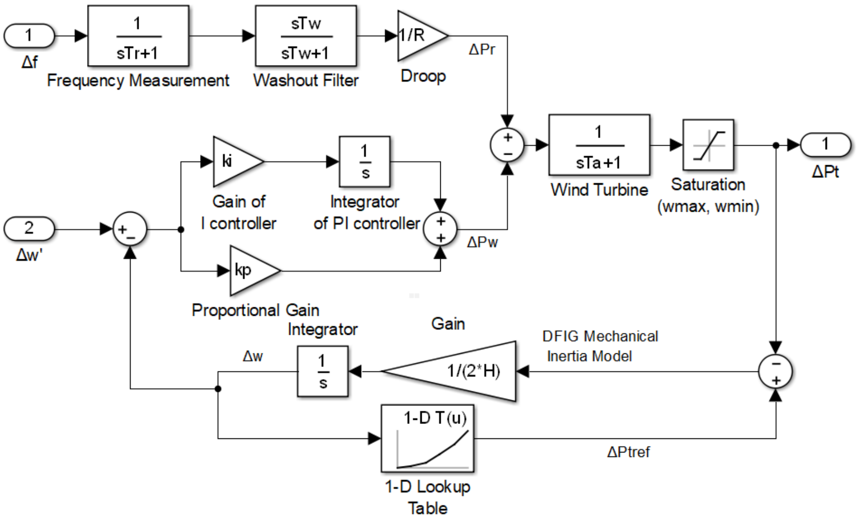

Figure 3.4 Primary-frequency-control and inertia control DFIG based wind turbine [108]

The power set point ΔPr is developed based on the rate change of the frequency deviation. Equation (11) [32] [32] describes the powerΔXr. Here Kdf and Kdp are the constants for 1st order frequency deviation derivative and Δf is the frequency deviation behind the high-pass filter. ΔPr is the output from this controller known as the reference power point (12) [119].

$$\Delta Xr = -Kdf\frac{d\Delta f}{dt} - Kdp\Delta f \qquad (11)$$

$$\Delta Pr = \frac{\Delta Xr}{R} \tag{12}$$

Here R is the conventional droop constant. The inertia constant of the large power plants is around 2-9 sec. The wind energy conversion system can achieve inertia constant of 2-6 sec through emulation of inertia. Hence to maximize the power output at the optimal speed additional control criterion can be adopted through the power reference ΔPw (13) [119] which is generated using measured speed and electrical power output. This additional controller can settle the speed quickly and reduces the transient period. Therefore the DFIG is suitable to achieve the required active power output and decrease the amount of deviation from the set point.

$$\Delta Pw = Kp(\Delta w' - \Delta w) + Kwi \int (\Delta w' - \Delta w)dt \tag{13}$$

$$\Delta Pfw = \Delta Pr - \Delta Pw \tag{14}$$

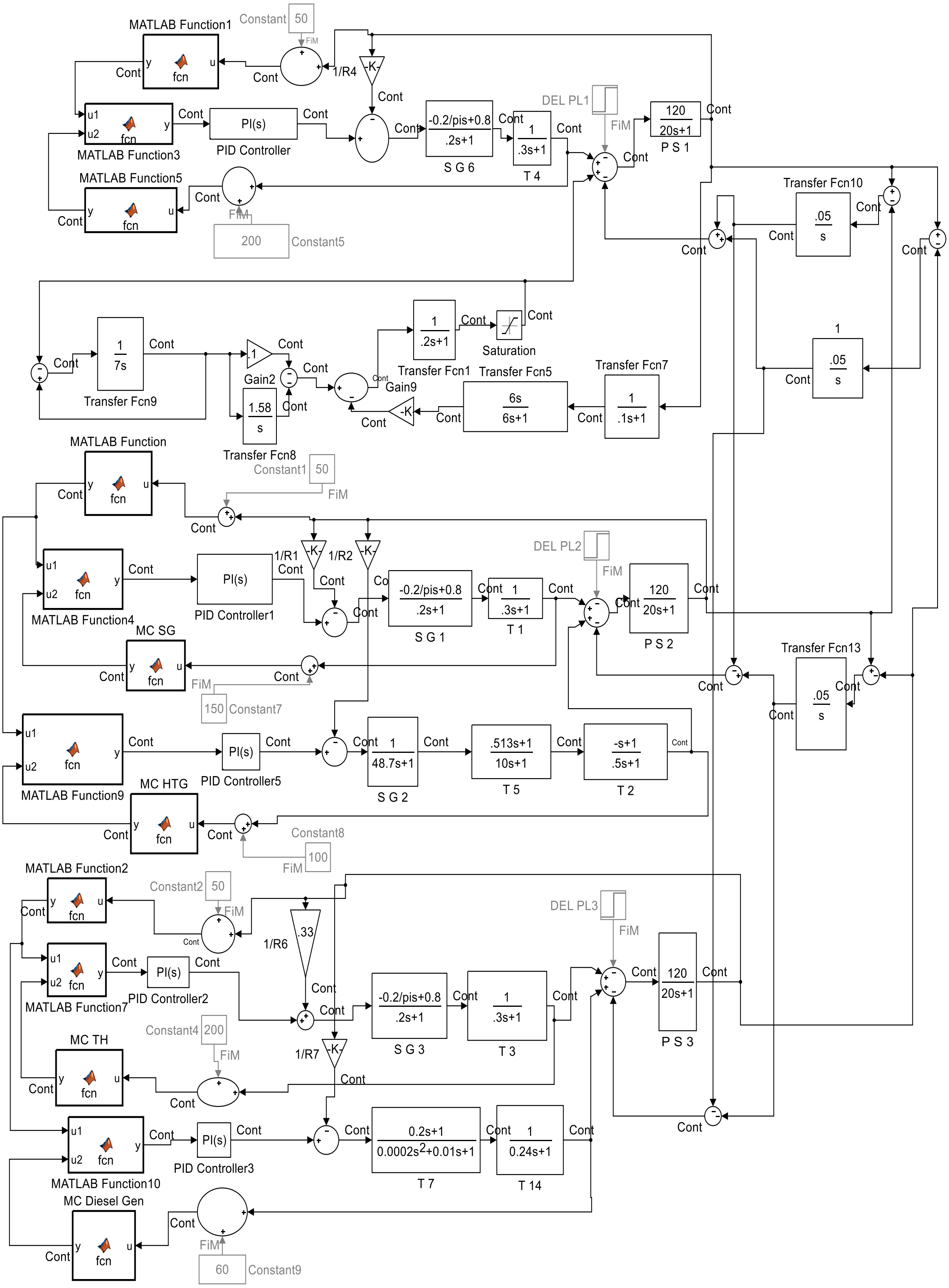

Figure 3.5 The thermal-hydro-wind-diesel/biomass hybrid power generation system developed in Simulink [108]

Here, Kwi and Kp are the gains of integral and proportional controller respectively. Equation (14) depicts the total active power reference for the wind generator. A PI controller is used to stabilize the frequency transient which occurs for a very short period of time compared to the time required for speed recovery. It is assumed that the PI controller output ΔPw will remain constant within few seconds and ΔPw remains constant during that short period. The high speed power electronic converter regulates the power generated by the wind turbine. No dynamics between ΔPr and the wind power output ΔPt is deliberated and the equation (15) is formed where ΔPt^{0} is the power injected prior to the frequency transient [119].

$$\Delta Pt = \Delta Pr - \Delta Pt^{0} \tag{15}$$

$$2H\frac{d\Delta f}{dt} = \Delta Pg + \Delta Pt + \Delta Ptie - \Delta PL - D\Delta f \tag{16}$$

The power system model depicted in Figure 3.4 is expressed in equation (16), where H and D represents conventional system inertia and the Now replacing ΔPt by (15) in (16) the equations (17) and (18) are obtained [119].

$$(2H' + Kdf)\frac{d\Delta f}{dt} = \Delta Pg + \Delta Pt^{0} + \Delta Ptie - \Delta PL - (Kdp + D')\Delta f \tag{17}$$

Or,

$$(2H)\frac{d\Delta f}{dt} = \Delta Pg + \Delta Pt^{0} + \Delta Ptie - \Delta PL - (D)\Delta f \tag{18}$$

$\mathrm{H}(= 2\mathrm{H}' + \mathrm{Kdf})$ is the new inertia and $\mathrm{D}(= \mathrm{Kdp} + \mathrm{D}')$ is the new frequency proportional term. This approach helps to contribute the inertia to the power system.

3.3.4 Transfer Function Model of Diesel Generator

The load frequency control model of the diesel/biomass generator is shown in equation (19). Here, the frequency error is amplified and a modified command signal is sent to the turbine governor. As the governor minimizes the difference between input and the output, the turbine output is changed. The gear changer of the diesel generator is controlled through the command signal set by the load frequency controller and in turn the diesel generator out is changed. The transfer blocks of the speed governing system and the diesel generator are shown in equation (19) and equation (20) [120].

$$G_{SGDEG}(S) = \frac{K_D T_{D1} s + K_D}{T_{D2} T_{D3} s^2 + (T_{D2} + T_{D3}) s + 1} \tag{19}$$

$$G_{DEG}(S) = \frac{1}{T_{D4} s + 1} \tag{20}$$

Here T_{D1}, T_{D2} and T_{D3} are the time constants of the speed governing system of the diesel engine generator. K_D is a fraction of power supplied to the load by the diesel generator. The individual models of the primary-frequency-control of the thermal, hydro, wind and diesel generators are now used to develop the ABT based secondary-frequency-control.

3.3.5 UI Price Based Secondary-frequency-control

As already discussed the Availability-based-tariff (ABT) structure has changed the two part tariff into three part tariff (capacity charge, energy charge and unscheduled interchange charge) in the Indian power sector. The capacity charge is a fixed charge which is paid to the utilities depending on the plant's availability over a period of time. It is linked to the plant availability. The scheduled generation and cost of the energy used determines the energy charge. The charge for deviation of scheduled generation from the actual one is the unscheduled interchange (UI) charge. This charge is linked with the frequency. The thermal, hydro and diesel/biomass generators connected in different areas follow the primary-frequency-control as well as in ABT based secondary-frequency-control in this case study. But, the frequency regulation of the wind turbine generator obeys the primary-frequency-control. The reason is the intermittent nature of the wind. Hence the ABT based secondary control has not been used for the wind generator. In all the three areas the deviation of actual frequency from the nominal frequency is calculated first. Then the UI is determined using the price-frequency relation as expressed in equation (21) [23]. Here λ is the UI rate vector in Paisa/kWhr or Rs./MWhr.

$$\Delta\lambda(s) = -K\Delta F(s) \tag{21}$$

3.3.6 MATLAB program to implement the ABT based frequency control

According to the ABT principle, during lean load period a plant generating less power than the scheduled will be paid for excess generation at higher UI rate. But it will be paid at lower UI rate for generating more during peak hour. Accordingly UI charge is calculated using

MATLAB code. MATLAB programs embedded in the Simulink model evaluate the generation control error. Incremental cost (Figure3.4) function calculates the change in marginal cost due change in generation i.e. incremental marginal cost of thermal, hydro and diesel/biomass power plants according to the plant's availability. The deviation of actual generation from the scheduled one is calculated as the unscheduled interchange. The UI rate as per the CERC regulation is used to decide the deviation charge. The block named Frequency to price conversion determines the change in real time pricing based on the deviation in the system frequency. Finally Generation control error block uses the output of the two earlier blocks and the generation control error (GCE) is calculated. The GCE signal is minimized through PI controller tuning. Thus the MATLAB functions embedded in the ABT based secondary control loop regulates the frequency of the renewable integrated interconnected three area power system. For minimising the GCE error PI controller has been used here.

The PID controller block of Simulink has been used here to implement the PI controller in the closed loop system. It is a weighted sum of the input signal and the integral of the input signal. These weights are the proportional and the integral gain parameters. The controller adopts parallel form and the parameters are set for continuous time domain operation. The controller coefficients can be tuned either manually or automatically. In the present work, the PI controller gains are tuned automatically which is supported by Simulink Control Design Software. To get better stability of the frequency, the settling time of the frequency deviation characteristic should be reach the nominal frequency quickly. This can be achieved only through proper optimization of the controller parameters. In the next case it is done through particle swarm optimization (PSO) technique which is a very good metaheuristic method for solving optimization problems [121,122]

3.4 Case4: Effects of Particle Swarm Optimization (PSO) with Time-Varying Acceleration Coefficients on Renewable Integrated Two Area Load Frequency Control under ABT

From case 1 to case 3, the frequency regulation and the tieline power fluctuations are observed for thermal-hydro-diesel/biomass system with or without renewable integration viz. the wind power using MATLAB/Simulink based controller tuning. The results obtained are of larger settling time. To reduce the settling time and get the quick stability in the frequency and other dynamic characteristics, the case uses Particle Swarm Optimization (PSO) with time-varying acceleration coefficients [112].

3.4.1 Two Area Hybrid Power System with Thermal-Hydro-Wind Generators

Only two areas have been considered for this study. Area 1consists of the thermal and wind power plants whereas the second area has one thermal and one hydro power plant. The transfer function blocks of the thermal, hydro and the wind power plants are already discussed in the earlier cases individually. The PSO based controller optimization technique is new to be added in the proposed block diagram of the entire ABT based frequency control system which is shown in Figure 3.5.

3.4.2 Unscheduled Interchange (UI) based Secondary-frequency-control using PSO

In this work, the grid discipline is maintained using proper frequency control mechanism through optimization of the controller gains. The objective of this case study is to get better dynamic response subjected to the load change. The secondary-frequency-control is achieved through the frequency-linked-pricing.

The capacity charge is determined based on the declared capacity i.e. availability of the power from a generator and the energy charge is calculated based on the fuel required for the scheduled generation of a conventional generator. The unscheduled interchange of power is linked with the frequency deviation feedback. From Figure 3.6, it is seen that the signal Δf is fed back to a MATLAB function block. The nominal frequency is 50 Hz. The UI price is calculated in Rs./MWhr. as per equation (22) and used the charges for frequency deviation as declared by the Central Electricity Regulatory Commission (CERC) [23]. This has been described in the previous sections.

$$\Delta\rho(s) = -k\Delta F(s) \tag{22}$$

$$C_{Th} = \alpha_i + \beta_i P_i \tag{23}$$

$$C_H = \gamma_i + \delta_i P_i \tag{24}$$

The incremental cost functions written in equation (26) and equation (27) describe the quadratic cost functions of the i^{th} thermal and the i^{th}hydro generators respectively. Here, α_i and β_i are the 1st order and the 2nd order cost coefficients of the thermal power plant respectively. Similarly, γ_i and δ_i are the 1st order and the 2nd order cost coefficients of the hydro-electric power plant respectively. The profits (PF_{Thi}) gained by the thermal or the profit (PF_{Hi}) gained by the hydro generator due to unscheduled interchange (UI) can be determined by equation (28) and equation (29) respectively; where the deviations in the marginal costs of the generators are presented as ΔC_{Thi} and ΔC_{Hi} .

$$PF_{Thi} = (\Delta\rho - \Delta C_{TH})\Delta P_i \tag{25}$$

$$PF_{Hi} = (\Delta\rho - \Delta C_H)\Delta P_i \tag{26}$$

The difference in the signals generated from the MATLAB function blocks which calculate the deviation in marginal costs and the incremental cost due to frequency deviations are used to determine the generation control error (GCE). The minimization of the GCE is necessary to control the generator output and in turn the frequency fluctuation. Here, the particle swarm optimization (PSO) technique has been used to optimize the PI controller gains. The optimized PI gains are used reduced the GCE signal and control the frequency fluctuation.

3.4.3 Calculation of PI Controller Gains with Particle Swarm Optimization (PSO)

In this application of the unscheduled interchange price based secondary-frequency-control, the gains of the proportional and integral controller (PI) are optimized using particle swarm optimization (PSO) technique. It is a meta-heuristics optimization technique which is developed following the behaviour of the individuals of a group. The individuals of the group or the swarm are known as the particles or agents [121, 122] of the group. This population based search process allows its particles to change their positions in the multidimensional search space. The reason behind such roaming or searching is to arrive at the optimum solution. The past experience of the particles and their nearby particles help to change the position of the particles.

3.4.3.1 Particle Swarm Optimization Technique

The mathematics of the PSO technique is described below.

The position vector and the velocity vector of a particle are defined first. Let the particle i in the group or the swarm of particles occupy the position vector

$X_i = (x_{i1}, x_{i2}, x_{i3}, \ldots, x_{in})$ and the velocity vector

$V_i = (v_{i1}, v_{i2}, v_{i3}, \ldots, v_{in})$

in the n dimensional search space.

Again, $Pbest_i = (Pbest_{i1}, Pbest_{i2}, Pbest_{i3}, \ldots., Pbest_{in})$ be the best position of the particle. The common best experience of all particles which is known as the global best and it is $Gbest_n$ (say). Now according to the memory the velocity and the position of each particle is updated using equations (27) and (28).

$$V_{in}(t+1) = w \times V_{in}(t) + c_1 \times r_1 \times \{Pbest_{in} - X_{in}(t)\} + c_2 \times r_2 \times \{Gbest_n - X_{in}(t)\} \quad (27)$$

$$X_{in}(t+1) = X_{in}(t) + V_{in}(t) \quad (28)$$

Here $i = 1,2,3, \ldots.., N_p$;$n = 1,2,3, \ldots., N_g$; N_p is the number of the particles. N_g is the numbers of elements in a particle i. the inertia term is represented using the symbol w. This inertia term is required to create the balance between the local and global search. The acceleration coefficients are c_1 and c_2. It is important to choose the coefficients c_1 and c_2 efficiently so that the particles to settle towards the local best position $Pbest$ and the global best position$Gbest$. Number of iterations is$t$. The uniform random numbers r_1 and $r_2$are chosen between 0 and 1. That is how normal particle based optimization is followed.

In this study some modifications on the PSO procedure described in section 3.5.3 has been applied and it is the use of the time varying acceleration coefficients to get better convergence.

3.4.4 Calculation of Time Varying Acceleration coefficients

As discussed in section 3.5.4, the stochastic acceleration coefficients c_1 and c_2 determines the convergence of the optimization problem. The second component of the equation (27) is called the cognitive component. The third component of the equation (27) is known as the social component. To arrive at the optimum solution these two components are needed to be controlled efficiently. In this modified PSO method, the particles do not move towards the population best, instead they move towards the search space. At the start they have larger cognitive components and the smaller social components. But, at the end the particles have the smaller cognitive components and the larger social components. The same is represented through the following equations. The time varying acceleration coefficients c_1 and c_2 are calculated following the equations (29) and (30) respectively. c_{1i} is the initial values of $c_1$and $c_{1f}$is the final value of c_1. Similarly c_{2i} and c_{2f} are the initial and the final values of c_2. Here, t_{max} is the maximum number of iterations;

$$c_1 = \left(c_{1f} - c_{1i}\right)\frac{t}{t_{max}} + c_{1i} \tag{29}$$

$$c_2 = \left(c_{2f} - c_{2i}\right)\frac{t}{t_{max}} + c_{2i} \tag{30}$$

Now, the old velocity vector presented in equation (27) is modified as (31) replacing c_1 and c_2 by the modified c_1 and $c_2$as indicated in equations (29) and (30).

$$V_{in}\,(t+1) = \left\{\left(c_{1f} - c_{1i}\right)\frac{t}{t_{max}} + c_{1i}\right\} \times r_1 \times \{Pbest_{in} - X_{in}(t)\} + \{\left(c_{2f} - c_{2i}\right)\frac{t}{t_{max}} + c_{2i}\} \times r_2 \times \{Gbest_n - X_{in}(t)\} \tag{31}$$

Most importantly the inertia constant w included in equation (27) is made equal to zero in equation (31). The premature convergence occurs in the conventional PSO technique at a local minimum if constant inertia constant is chosen. As discussed earlier in this section that zero inertia constant can help the particles roam the entire search space and reach the local

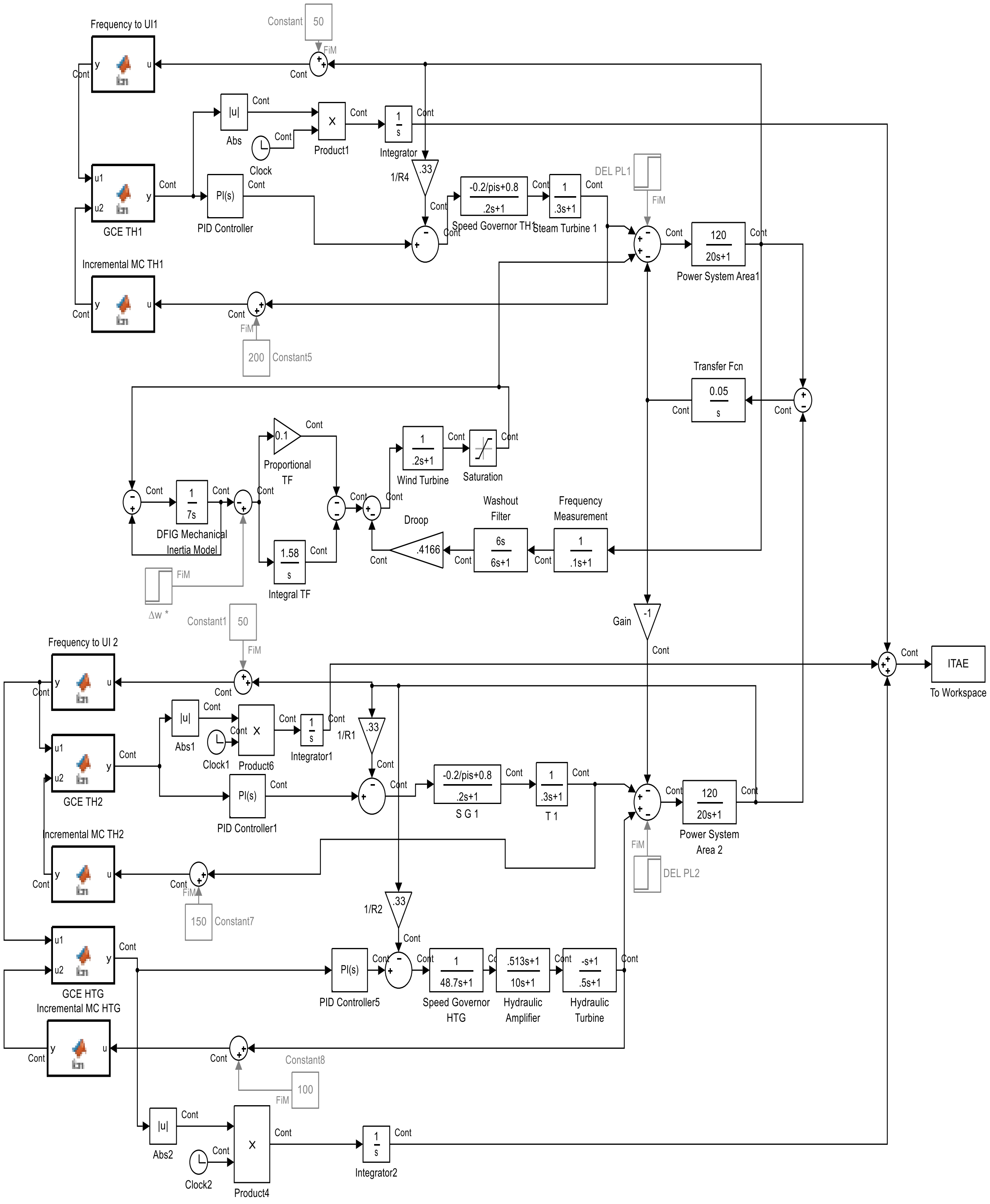

Figure 3.6 Block Diagram of the proposed Thermal-Wind-Hydro based two area interconnected-power-system [112]

optimum solution quickly. This leads to the early converge. To get the optimum solution we have to choose the initial population carefully.

In the next case study the effect of the wind penetration in the interconnected-power-system frequency regulation, generations and the UI rates are investigated.

3.5 Case 5: Wind Power Penetration Effect on the Unscheduled Interchange (UI) Rate in an Indian Two Area Interconnected-power-system

In the fifth case we have studied the frequency regulation of an interconnected hybrid power system having wind power generator. In this case, the effect of wind power penetration on the frequency fluctuations and the generation of power from other generators are addressed [111]. It affects the demand system, performance of the generator and grid operation. The system adopted is same that of the earlier case, only the information gathered here is not available in any other literature. The effects of wind power penetration on the UI prices are investigated in this section along with the frequency stability due to load perturbations. For this purpose the grid stability in the ABT environment needs discussion.

3.5.1 Grid stability under ABT Regime

The interconnected power in the Indian context is studied for the frequency regulation under ABT regime in this work. The proposed power system is integrated with the wind power generator whose availability cannot be declared day ahead. Wind turbine generator (WTG) output is subjected to the intermittent wind speed. Hence to study the grid stability for interconnected-power-system, the wind generator has been kept outside the ABT loop. For the thermal, hydro and the diesel/biomass generators UI price based frequency control criterion has been applied in the secondary-frequency-control loop. Here the conventional generators are incentivised if they generate more power during peak demand to keep the frequency at 50.0 Hz. But they are penalised if they generated more power during the lean hours. The frequency regulation is important as frequency deviation can cause damage to the large industrial power consumers. Such frequency fluctuations can result in the network failure, generator tripping, power failure etc. Hence thus this proposed scheme can solve the problem of grid indiscipline in terms of the frequency fluctuations both technically and economically under ABT regime.

3.5.2 Generation Scheduling of the Generators

The declared scheduled capacity to deliver the ex-bus power output to the grid is termed as the availability of the generator. The availability of generated power of a thermal power plant for any time period can be defined as “the percentage ratio of average generation of all time blocks during the said period and the rated output capacity” of the power plant. There are 96 time blocks of 15 minutes duration in each day for which the plants have to declare their generation capacities in MWHr. in Indian power sector. The hydel power plants declare the MWHr delivery for that day. Hence the generation scheduling of the thermal and the hydro power plants are done. The central and the intra-state power system follow ABT rule in India. The next section shows the UI pricing for the proposed system.

3.5.3 Unscheduled Interchange Pricing Calculation

According to the UI rule, the UI price, ρ for each generator is noted and it is compared it with the marginal cost of generation, γ. The deviation of the UI price from the marginal cost is termed as the Generation Control Error (GCE) signal. This signal is equivalent to the area control error (ACE) of the AGC system. The GCE is minimised using the appropriate proportional-integral (PI) controller parameters. If the error signal GCE is positive, the generator can benefit by increasing the generation. But if it is negative, the generator has to reduce the generation to earn profit. Thus by controlling the power generation as per ABT rule the generators can earn profit.

The difference between the Actual-Generation (AG) and the Scheduled-Generation (SG) [123, 124] determines the UI charges. The rate is calculated using the average frequency at that particular time block. The actual-generation (AG) is obtained from the average generation for a particular time period of 15 minutes. The AG is higher than SG, when the system frequency is less than the nominal frequency, the generator is incentivised when the generation is increased and it improves the frequency [123]. But when the grid frequency is low and the AG is still less than the SG, then the generator will be penalized. If the system frequency is same that of the nominal frequency then the low AG is preferred. The utility gets the reward through the payment of the running (C_R) cost (32) on SG for that period.

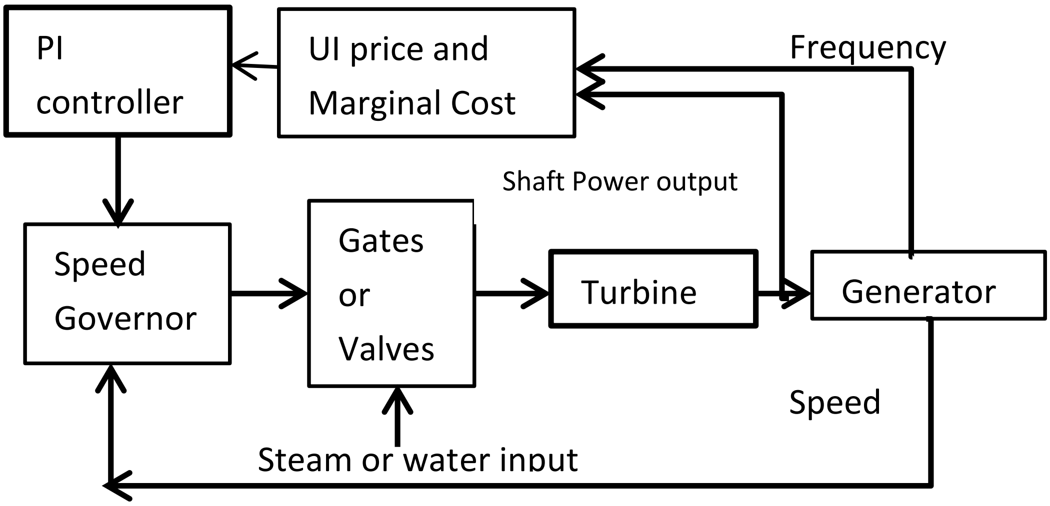

Figure 3.7 Price based Automatic Generation Control for conventional generators

$$C_R = CR_E \times \sum_{i=1}^{N} SG_i \qquad (32)$$

The monthly UI charge (33) is

$$C_{UI} = \sum_{i}^{N} \sum_{j=1}^{N=96} (AG_{ji} - SG_{ji}) \times R_{UI\ j} \qquad (33)$$

Here, C_R=Running Charge, CR_E=Energy Charge Rate, Rs./MWHr, SG=Scheduled generation in MW, N=No. of Days in a month, C_{UI}=Unscheduled Interchange Charge, R_{UI}=Rate of Unscheduled Interchange in Rs./ MWHr.

The system configuration remains the same that of Case 3 (Figure 3.4).

The next focus is on the incorporation of the microgrid in the one of the interconnected area of the proposed power system.

3.6 Case6: Study of Grid Discipline in an Interconnected-power-system incorporated with Renewable based Micro-grid Under ABT

In the previous five cases, the system configurations are restricted to the hybridization of the thermal, hydro, diesel/biomass and wind power generations in two or three or four areas. In the present case, along with the previously mentioned generators one microgrid is also considered to be in operation in one area along with a thermal generator. The microgrid consists of the distributed generators, storage devices, control and coupling elements. Here the components of the microgrid are offshore wind generator (WTG), fuel cell (FC), aqua electrolyser (AE), diesel generator (DEG), flywheel energy storage (FESS) and battery energy storage system (BESS). As a microgrid does not show the ideal properties of a restructured system, here it is considered as a generator and kept outside the frequency linked secondary control loop.

3.6.1 System Configuration of the proposed Thermal, Hydro, Diesel/Biomass based Microgrid system

Three area interconnected-power-system (Figure3.7) has been considered for this investigation. Area1 has two thermal power plants whereas area 2 has one thermal power plant and one hydro plant. Area 3 is different from the rest; it consists of one thermal plant and one micro grid. Since the emphasis is given nowadays mostly on renewable generation, this work includes renewable resources as the components of microgrid. Hence they together are considered as a “generator”. The microgrid has replaced one of the generating units of the interconnected-power-system in this investigation. The individual transfer function models of thermal and hydro generators participating in the interconnected-power-system are discussed in the following sub sections. The components of the microgrid in the form of transfer function models are also described here.

To study frequency control of the interconnected-power-system incorporated with RE based interconnected-power-system, the transfer function model of the individual generators and the components of the microgrids are required to be modelled which is done next.

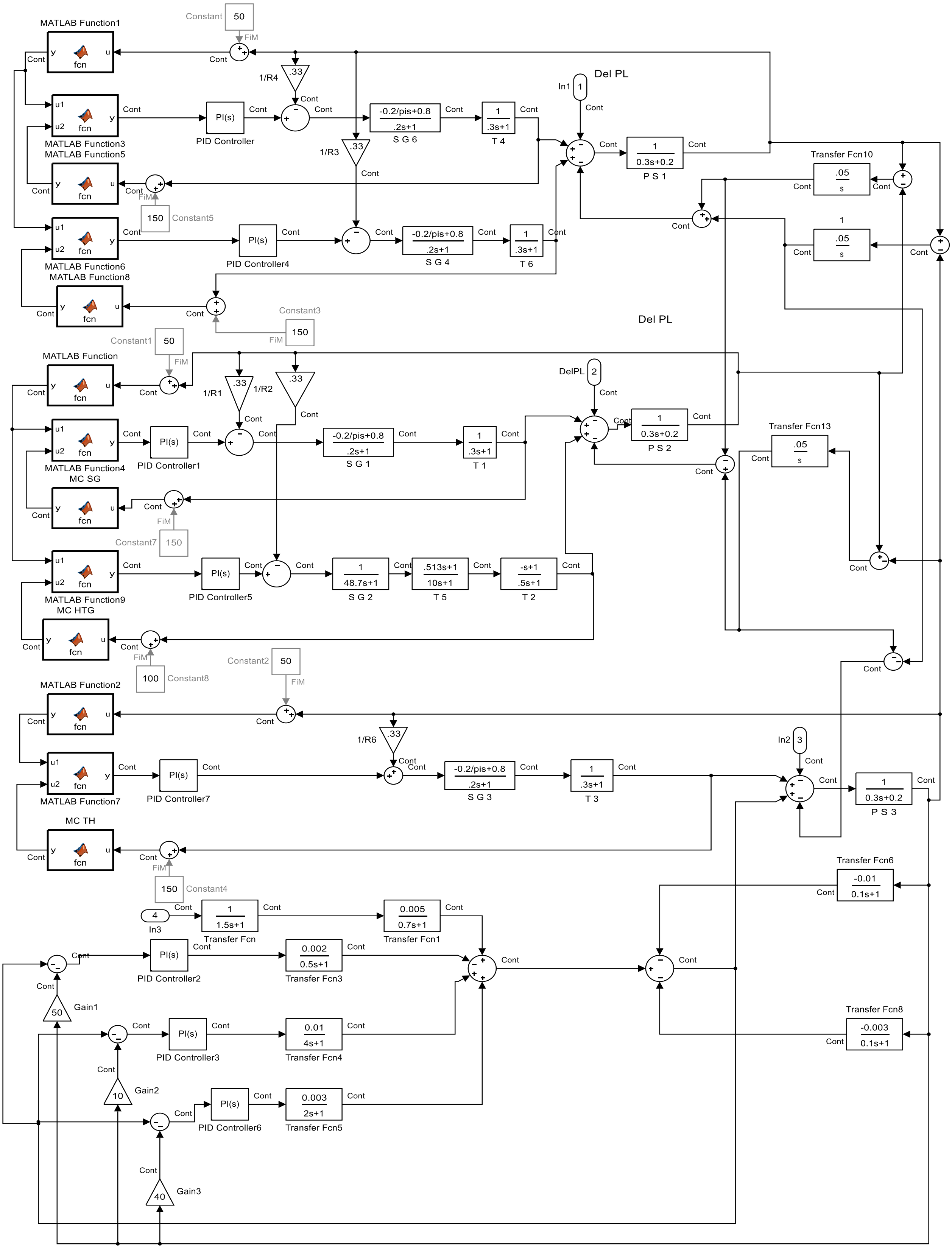

Figure 3.8 ABT based interconnected three area power system incorporated with Microgrid developed in MATLAB/Simulink

3.6.2 Transfer function model of the Thermal Generator

The speed governor (34) transfer function in series with the steam turbine transfer function (35) constitute the transfer function model of the thermal generator [125, 114] working in the primary-frequency-control loop. A dead band of 0.05% is adopted for the speed governor transfer function.

$$G_{SG}(S) = \frac{-K_2 / \omega_0 s + K_1}{T_{sg} s + 1} \tag{34}$$

$$G_T(S) = \frac{1}{T_t s + 1} \tag{35}$$

Here $K_1$and K_2 are the governor dead band block constants, T_{sg} and T_t are the time constants of the speed governor and the steam turbine respectively.

3.6.3 Transfer Function model of Hydro Turbine Generator

The hydro generator connected in the proposed interconnected-power-system operates under primary-frequency-control loop as well as the unscheduled interchange based secondary-frequency-control loop. The water inertia, compressibility, gate position, pipe wall elasticity of the penstock etc influence the performance of the hydro turbine. The primary-frequency-control loop regulates the gate position, droop compensation and water inertia. The transient droop is compensated through dashpot. The rate feedback plays an important role to achieve temporary transient droop and the resetting time. Finally the hydro turbine output is obtained through the speed governor, the hydraulic amplifier and the hydraulic turbine output control mechanism as shown in (36), (37) and (38) [114, 125].

$$G_{sgh}(S) = \frac{K_{sgh}}{1 + sT_{sgh}} \tag{36}$$

$$G_{ha}(S) = \frac{1 + sT_r}{1 + ST_{ha}} \tag{37}$$

$$G_{ht}(S) = \frac{1 - sT_w}{1 + s0.5sT_w} \tag{38}$$

Here T_{sgh} is the time constant of hydraulic speed governor, K_{sgh} is the gain and T_r is the reset time. T_{ha} is the hydraulic amplifier time constant and T_w is the water starting time required for the water head in the penstock to achieve a steady velocity.

3.6.4 Transfer Functions of the Constituents of the Proposed Microgrid

The microgrid depicted in Figure3.8 acts as a generator and participates as the primary-frequency-control element. As most of the components (especially the wind generator) are based on renewable energy resources, the availability of the microgrid is intermittent. Hence its components are not participating in the ABT based secondary-frequency-control. In this part, the system modelling does not include the non-linarites of the generators, hence 1st order linear transfer functions has been adopted for all microgrid components

To investigate the change in grid frequency and tie-line power flow, the transfer function models of wind, fuel cell, diesel generators etc are described next.

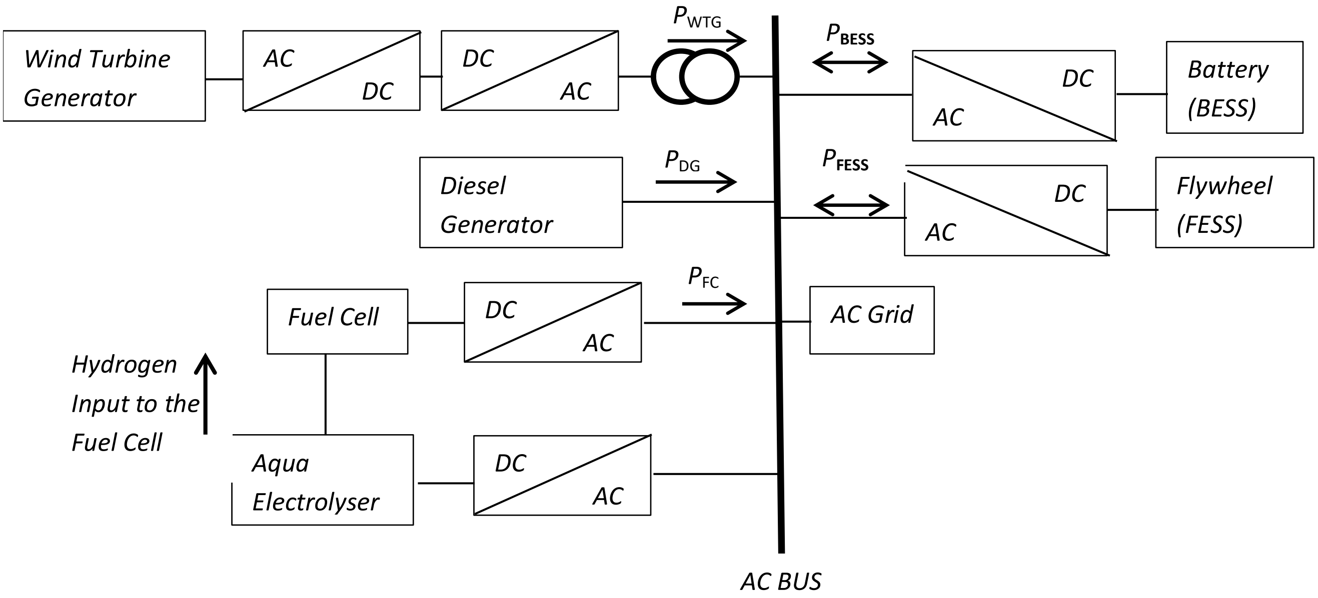

Figure 3.9 Schematic Diagram of renewable energy (RE) based Microgrid

3.6.4.1 Wind Turbine Generator (WTG)

The output of wind generator is dependent on wind speed comprising the base wind speed, ramp wind speed, gust wind speed and noise wind speed [38]. The wind turbine output (39) is express as

$$P_v = \frac{1}{2}\rho A_r C_p V_w^3 \tag{39}$$

Where ρ is the air density in kg/m^2, and A_r is the swept area of the turbine blade in m^2. C_p is the power coefficient and it is the function of the ratio of tip speed and blade pitch angle. The transfer function of the wind turbine generator (40) is expressed as

$$G_{WTG} = \frac{K_{WTG}}{1 + sT_{WTG}} \tag{40}$$

K_{WTG} and T_{WTG} are the gain and the time constant of the wind turbine generator respectively.

3.6.4.2 Diesel Generator (DEG)

It is preferable to have a standby generator in a renewable based DG. Mostly this is a diesel generator. During the non-availability of the wind power, DEG (41) [99, 109] can meet the demand. It is modelled as shown in equation (41)

$$G_{DEG} = \frac{K_{DEG}}{1 + sT_{DEG}} \tag{41}$$

K_{DEG} and T_{DEG} are the gain and the time constant of the diesel generator.

3.6.4.3 Fuel Cell (FC)

Fuel cells are the producers of clean power. It converts the chemical energy of a fuel into electricity through the chemical reaction of the hydrogen ion with the oxygen or any other oxidising agent. Depending on type of electrolytes used fuel cells are commonly classified as Proton Exchange Membrane (PEMFC), Alkaline (AFC), Solid Oxide (SOFC) Phosphoric Acid (PAFC), Molten Carbonate (MCFC) etc. The transfer function of FC (42) [10, 126] can be written as

$$G_{FC} = \frac{K_{FC}}{1 + sT_{FC}} \qquad (42)$$

K_{FC} and T_{FC} are the gain and the time constant of the fuel cell respectively.

3.6.4.4 Aqua Electrolyzer (AE)

Aqua electrolyser uses a part of power output from wind generator and produces hydrogen which is one of the key fuels of fuel cell. The 1st order transfer function of AE (43) [10, 126] is shown below

$$G_{AE} = \frac{K_{AE}}{1 + sT_{AE}} \qquad (43)$$

K_{AE} is the gain and T_{AE} is the time constant of the aqua electrolyser used here.

3.6.4.5 Energy Storage System (ESS)

In hybrid renewable based DG the presence of energy storage system is indispensible. Hence the flywheel energy storage system (FESS) and battery energy storage system (BESS) are used. FESS stores mechanical energy in the flywheel system and converts it into electrical energy as and when required. It offers high power density, efficiency compared to batteries and emits no hazardous chemicals. It is modelled (44) [10] as

$$G_{FESS} = \frac{K_{FESS}}{1 + sT_{FESS}} \qquad (44)$$

Here, K_{FESS} is the gain and T_{FESS} is the time constant of the flywheel energy storage system. Battery energy storage system (BESS) consists of battery banks connected to the AC bus through power electronic converters. During light load period, these converters convert the AC power to DC power to charge the BESS and convert the DC power of the BESS to AC power to supply the load during the peak load period. The BESS is mainly used for load levelling, voltage control, harmonic rejection etc. Its 1st order transfer function [126, 127] is shown in (45).

$$G_{BESS} = \frac{K_{BESS}}{1 + sT_{BESS}} \qquad (45)$$

Here, K_{BESS} is the gain and T_{BESS} is the time constant of the battery energy storage system.

All the transfer functions described here are incorporated in the ABT based secondary control system.

3.6.5 ABT based Control

The ABT based secondary control and Free Mode of Governor Operation (FMGO) for primary-frequency-control has been adopted for conventional generators used here. But for wind turbine generators separate scheme has been applied. Doubly Fed Induction Generator (DFIG) is chosen for generation of electricity from wind power. DFIGs are connected to the grid through static converters. Hence they do not contribute to the grid inertia directly. Therefore the huge kinetic energy stored in the wind turbine blades contributes as the hidden inertia of the wind turbine generator set. The pitch control and static converter control together form the frequency control which in turn regulates the active power output. Thus the primary-frequency-control adopted here operates to facilitate the output power and rotor speed following the de-loaded optimum power extraction characteristics. No availability based secondary control can be adopted as input to the wind turbine is intermittent. Marginal cost function is required to evaluate the GCE. So the next section discusses the calculation of the marginal cost in this case.

3.6.5.1Marginal Cost Calculation

In availability-based-tariff structure, the availability of power from a generating unit determines the capacity charge. The second part of this tariff i.e. energy charge is calculated based on the fuel required to meet the scheduled generation [2, 126]. Therefore the thermal and hydro generators [115, 125] follow the quadratic cost functions. The cost per unit of power generation from these two conventional generators are shown in (46) and (47)

$$C_{th} = A_i + B_i P_i \ in\ Rs./MWh \qquad (46)$$

$$C_h = D_i + E_i P_i \ \ in\ Rs./MWh \qquad (47)$$

A_i and B_i are the 1st and 2nd order cost coefficients of i_{th} thermal plant respectively whereas D_i and E_i are 1st and 2nd order cost coefficients i_{th} hydro plant respectively.

Under ABT rule the calculation of the UI price is mandatory which is described next.

3.6.5.2 Unscheduled Interchange Price

Unscheduled interchange (UI) plays an important role in frequency control these days. The deviation of the actual generation from the scheduled one is considered as the unscheduled interchange. The price rate fixed for such unscheduled interchange in definite interval of time is regulated through CERC [23]. This work has used this rate for calculation of UI price at the working frequency. In turn this is fed back to the MATLAB/Simulink function block for calculation of the error signal. Thus the secondary-frequency-control loop accommodates the UI based control. In this mechanism over injection by the sellers (generators) during grid frequency above 50.0 Hz are penalised and the over injection by the plants during grid frequency below 50.0 Hz is incentivised. This ABT principle is used to evaluate UI charge through MATLAB code. The error signal generated is fed through a PID controller which is tuned using Ziegler-Nichols [128] method and the gains are obtained using MATLAB program.

It is described next.

3.6.5.3 Ziegler Nichols (ZN) based PI Controller Tuning

The Ziegler-Nichols (ZN) tuning method [128] is a well-established method for tuning PID controller. In the price based secondary-frequency-control loop PID controller is implemented using this method. As PI controller is the most efficient form of PID controller, this work has also adopted the same. It is performed by setting the integral value to zero first and then increasing the proportional controller gain from zero to a value Ku where the stable output is obtained. But an oscillation is introduced. To reduce it integral controller gain is set and the overshoot is controlled. Let the oscillation period be Tu. Now, if M is the amplitude ratio, then as per ZN method K_u is set as $1/M$. K_p, K_i and T_i are set as follows

$$K_p = 0.45k_u, T_i = 0.8T_u \ and\ K_i = 0.45K_u/T_u \qquad (48)$$

Following the above (48) rule the PI controller is tuned. The values of controller gains are shown in the block diagram for each loop.

The problem formulations described in this chapter are used to solve the case studies in MATLAB/Simulink platform. The solution methodologies adopted to solve these cases are described in chapter 4.

Chapter 4: Solution Methodologies

In the previous chapter 3 six pertinent issues related to the knowledge gap that exists have been identified and vis-a-vis the corresponding technical formulations of such technical gaps have been developed. In this chapter attempts will be made to identify the methodologies of solutions encompassing those six issues singularly, but with an inherent flow of logic connecting them. In section 4.1 the frequency regulation of thermal-hydro-diesel/biomass based three area interconnected-power-system has been investigated using UI pricing criterion under ABT scheme.

4.1 Secondary-Frequency-Control of Three Area Thermal-Hydro-Diesel/Biomass Hybrid Power System based on Unscheduled Interchange (UI) Price

A three area interconnected hybrid power systems having thermal, hydro and diesel generators are combined to supply power to each area. The areas are connected through tie-lines among themselves as shown in Figure 3.1. Some parts of India are rich with hydro potential, while some with coal reserve or monsoon driven hydro potential etc. Therefore system adopted here is quite feasible and compatible to different scenarios. Though the plant capacity of diesel generator is less compared to the hydro and thermal plants, its introduction is justified in the sense that in future the diesel can be replaced by bio-diesel or biomass using proper biomass *gasifier*. However though the system is interconnected, considerations are not provided here for a deregulated system.

In this case, the model of three area interconnected-power-system has been developed in the MATLAB/Simulink environment. Individual transfer functions as described in section 3.1 are first drawn with the chosen values of the coefficients indicated in that section. Then the transfer functions of the individual generators are interconnected in each area and areas are linked with the tie-lines. The main difference of the proposed system from the conventional secondary load frequency control system is that the frequency deviation is converted to the UI charge in Rs./MWHr following the Table 3.1. Similarly the deviation of the actual generation from the scheduled generation is also calculated. Then the generation control error

(GCE) is evaluated and this error is operated with the Proportional and Integral Controller (PI) controller so that the error is minimised. Thus the actual generation is controlled and the frequency reaches the set value. Since the plant coefficients and the other plant parameters as provided in section 3.1 are taken for a Indian system, the synchronous grid frequency is considered as 50 Hz.

In the next the numbers of interconnected areas have been increased to four a case as described in section 3.2 to study the effects of the tie-line connection/disconnection effect on the other areas under ABT.

4.2 Application of UI Price based Secondary-frequency-control on a Four-Area Hybrid Power System and its Effects on Tie-line Power Flow

In this work, a four area interconnected-power-system having thermal, hydro and diesel/biomass power generations are considered. The secondary load frequency control based UI price is used here to study the step load perturbations with all area interconnected as well as with area1 being disconnected from others. The effects of such situations on tie-line power flow between areas and also on frequency deviations are observed consequently. The potential of fossil fuel based power generation is the highest in India, major plants opted here are thermal plants. Next choice is the hydel plant followed by diesel/biomass power generation. Area1 consists of two thermal generators whereas area 2 has one thermal and one hydro generator. Area 3 and area4 have the combinations of thermal-diesel/biomass and hydro-diesel/biomass respectively. The primary-frequency-control of each area is based on speed governor control. But the secondary control is unscheduled interchange (UI) based price control.

The solution methodology set for this case study is similar to that of the earlier one. Here I have increased the numbers of the areas so that I can study the effects of the unscheduled interchange prices on the tie-line behaviour when different generators are disconnected due to different natural causes which occur frequently in power system operation. At the same time the generation deviations due to load changes in the power system areas are also studied and its effects on the grid discipline are also investigated. The corresponding results are shown in the next Chapter.

4.3 Frequency Regulation of Thermal-Hydro-Diesel/biomass-Wind Power Integrated Indian Power System under Availability-based-tariff

An interconnected-power-system having different energy sources need proper control of frequency and tieline power flow. When renewable energy sources of intermittent nature are integrated with the power grid, fluctuations are inherited immediately which may lead to the instability of grid operation. In Indian power sector around 56.8% of total power is generated from fossil fuel and 11.2% is generated from hydropower. In both the cases the synchronous generators are used to convert the steam power or the hydropower into electricity. These rotating machines along with other motors like synchronous or induction motors connected with the grid gives the enough inertia to restrict the frequency fluctuations. For the purpose the primary-frequency-control systems are adopted which have already mentioned in Chapter 3. The lack of the inertia problem arises when the non-fossil fuel based power generators are integrated with the grid through the static converters. In India the share of the non-fossil fuel power generation is about 43% among which solar, wind and other renewable energy (RE) based power generation is almost 30.2%. The reduced inertia problem is mitigated here through emulating inertia based primary-frequency-control of wind turbine generator. But, the problem of the intermittent nature of the wind speed restricts to set the declared availability day ahead for the wind generators. Hence the wind generator frequency control scheme has been limited to the primary-frequency-control and not included in the UI price based secondary-frequency-control.

To achieve the sustainable operation and economic trading of power between seller and buyer and to maintain the grid stability, the secondary-frequency-control can be imposed through unscheduled interchange (UI) in the availability-based-tariff regime. This work has applied the unscheduled interchange based secondary-frequency-control in a hybrid power generation system with thermal, hydro, diesel/biomass and wind power for an interconnected three area power system in an Indian context. The block diagram of the proposed interconnected system has been depicted in Figure 3.4. The corresponding transfer functions developed in the MATLAB/Simulink software. The effects of integration of wind and diesel/biomass with conventional power sources on frequency and tieline power flow for sudden changes in power demands have been investigated here. Effects of withdrawal of wind or diesel/biomass generator are also studied for perturbed load condition. Finally the unscheduled interchange prices are calculated.

The need of the optimization of The PI controller has been identified as the response time of the frequency, generation and the tie-line power deviation characteristics are large. To reduce the settling time the PI controller gains are tuned through particle swarm optimization technique. The next section has focused on the development of the PSO algorithm as applied here.

4.4 Effects of Particle Swarm Optimization (PSO) with Time-Varying Acceleration Coefficients on Renewable Integrated Two Area Load Frequency Control under ABT

In the previous works, the frequency-linked-pricing based stability control schemes are solved. The frequency deviation characteristics and the tie-line power deviation characteristics thus obtained in GCE based frequency control system show larger settling time compared to that of the ACE based load frequency control scheme. Hence, it is necessary to optimize the GCE based system using an optimizing technique. For the purpose, Particle Swarm Optimization (PSO) technique has been chosen and implemented in a renewable based hybrid power system in availability-based-tariff (ABT) regime. The frequency deviation, tie-line power deviation or the changes in the power generation characteristics settle very quickly compared to the normal iterative method of tuning of the PI controller as applied in the earlier cases. The process adopted to link the optimization program and the interconnected-power-system model simulation can be treated as a novel approach for solving the GCE based system. The choice of the time varying acceleration constants in the PSO program which can decrease the convergence time and improve the system response has led to the better results. The MATLAB scripts linking the proposed two-area thermal-wind-hydro based hybrid interconnected-power-system with the optimization algorithm has been developed in-house which is described next.

4.4.1 Proposed Algorithm to Optimize the PI Controller Gains

The particle swarm optimization (PSO) technique with time varying acceleration coefficients has been applied to optimize the proportional-integral (PI) controller gains. In this problem, the generation control error is minimized using the optimal values of the PI gains. From the block diagram of the interconnected-power-system it is clear that the equation (27) is solved using the program written in the “Frequency to UI 1” MATLAB function block. Similarly, another program written in “Frequency to UI 2” MATLAB Function is executed. Both the functions use the UI rates imposed by CERC [28, 29]. These are the conversions of the deviation of the actual frequency from the nominal grid frequency into the unscheduled interchange price. The generation deviations are also taken into the account during the feedback process. The incremental marginal costs for two thermal generators are evaluated using the MATLAB Functions “Incremental MC TH1” and “Incremental MC TH2” respectively. Similarly the incremental marginal cost of the hydro turbine generator is also calculated using the MATLAB function block named “Incremental MC HTG”. All these MATLAB function blocks are developed in-house. The output signals of Frequency to UI block and the Incremental Marginal Cost block are used to calculate the generation control (GCE) for the thermal and the hydro generators.

Next is the application of the PSO in optimizing the PI gains. For this purpose, the absolute value of GCE is taken and multiplied with the clock. Then the multiplied signals are integrated. Same mathematics is applied for two thermal generators and one hydro turbine generator. Then, using the summation block these three functions are added and the result is fed to the MATLAB workspace. This function transferred to the MATLAB workspace is optimized using “ITAE”. Thus the fitness function to be optimized through the PSO technique is developed.

There are three proportional-integral (PI) controllers. Each one has one proportional and one integral gain. Therefore it is needed to optimize three proportional gains and three integral gains. The next step is to establish the link between the proposed block diagram of the thermal-hydro-wind based two area interconnected-power-system under availability-based-tariff regime and the PSO based MATLAB script this is the most important part of this case study. The PSO program fixes the values of all the six proportional-integral PI gains. In each iteration once these six values are generated, they are communicated to the block diagram develop in the Simulink. Again a new GCE signal is developed and through the intermediate program "ITAE" i.e. the Integral time Absolute Error function is evaluated. Thus for every iteration the new sets of PI gains determine the frequency characteristics, tie-line power characteristics and the generation deviation characteristics. Once the convergence of the PSO program is achieved the final PI controller gains determine the steady vales of the frequency deviation, tie-line power deviation and the changes in the generations.

As applied to this case study, the number of decision variables is six (6). There are one proportional gain and one integral gain of the PI controller used for three conventional generators (two thermal generators and one hydro generator). Thus six gains of all the PI controllers are to be optimized. To proceed with the solution, I have considered the population size i.e. the swarm size to be 50. The population members are initialized after initializing the position vector, the velocity vector, the fitness function, the best position and the best fitness. The earlier case studies have given the ideas about the values of the PI controller gains. That time, those gains are evaluated using the iterative method and the settling times are not satisfactory [124]. From those results the idea of minimum and the maximum values of the variables are chosen. These limits are used in the PSO program. The algorithm developed for the PSO program is written below.

1. Each particle is initialized for its position, velocity, fitness, best fitness, best position and the population array. The population members are also initialized.
2. The function "ITAE" is used to calculate the Fitness function for each particle.
3. When this fitness value of each particle is better compared to the best value in the history, then the best position or the Pbest takes the present value.
4. The particle positions are modified according to equation (28) satisfying the constraints.
5. The values of the time varying acceleration coefficients c_1 and c_2.are evaluated following the equations (29) and (30) respectively.
6. The particle velocity is revised following the equation (31).

7. The particle having the best fitness value is considered as the Global best i.e. the Gbest.
8. The program terminates at step 8 when the maximum iteration number is attained, else it returns to step 4.
9. The final Gbest or global best is the solution of the program.

The wind power has been already included in the interconnected-power-system. But the effect of its penetration in the power system has not been considered. The next section discusses the solution methodologies adopted to study the same in a three area thermal-hydro-diesel/biomass-wind integrated hybrid power system.

4.5 Wind Power Penetration Effects on the Unscheduled Interchange Rate in an Indian Two Area Interconnected-power-system

The ABT related frequency control method is suitable for maintaining the grid discipline and the economy from the buyers' and the seller's perspective. The cost functions of the conventional generators are well established but the related cost functions of the RE generators are not defined properly as these sources are intermittent in nature. The renewable energy based power generators do not contribute to the grid inertia as they are mostly connected with the grid through the static converters specially the wind turbine generators (WTG). So if the RE penetration is increased in the grid then there exist a problem of low inertia. This leads to the grid instability, frequency fluctuations and poor dynamics in the generation characteristics. Hence through the use of emulating inertia in the primary-frequency-control of renewable generators like wind turbine generators this has been compensated. The details of the primary-frequency-control of the WTG have been shown in section 3.4. In this work, among several renewable power generations, the wind power has been chosen for an Indian interconnected-power-system to investigate the wind penetration effect on the reduction of the frequency fluctuations. The wind power penetration also affects the unscheduled interchange (UI). This study also finds the frequency deviation and tie-line power flow characteristic for changes in the load. Here, the rates of UI prices of the generators are noted for different amount of wind penetration in the proposed thermal-hydro-diesel/biomass-wind based power generating system. This approach can help to control the grid frequency and maintain the grid discipline for more RE integration in future. The MATLAB/Simulink has been used to model the proposed system using the in-house program.

To solve the problem, the primary-frequency-control and the unscheduled interchange based secondary control loops are modelled in MATLAB/Simulink platform. The unscheduled interchange price based Generation Control Error (GCE) signal is generated first. To minimize it the PI controllers' parameters are tuned using Simulink's internal tuning method. Separate MATLAB scripts are written for each of the thermal, hydro and diesel/biomass generators which convert the frequency deviation to UI charge. It also determines the Incremental Marginal cost and the GCE signal separately. The frequency regulation and the tie-line power deviation characteristics are investigated for sudden change in demand which is modelled mathematically with the step function. The change in the wind penetration is also considered.

The need for using the microgrids has been described in the second chapter. In the next section the frequency stability of the microgrid incorporated interconnected-power-system has been studied.

4.6 Study of Grid Discipline in an Interconnected-power-system incorporated with Renewable based Micro-grid Under ABT

In the earlier applications the frequency regulation and the tieline power fluctuations have been studied for the multiarea area interconnected-power-system under ABT regime. In Indian sub-continent the wind power generation are effective. Till date almost 11.2% of total generated power is from wind power. Especially the off-shore wind generators are more efficient than the wind turbine generators installed on the main land. So along with the hydro and thermal generations wind power are hybridized to supply the grid in the earlier works. Hence the combination of conventional power generation from fossil fuel and hydro along with a microgrid having wind and other renewable energy resources are attempted in this part of the thesis. This proposed system has incorporated a microgrid in one of the three areas.

One of the components of the microgrid is the off-shore wind farm. It has been considered here as the generation capacity of off-shore wind plants are more compared to the on-shore plants. Other components of the proposed incorporated microgrid are one fuel cell (FC) and the energy storage devices like FESS and BESS. The later components of microgrid are chosen to combat the intermittent nature of the wind speed.

The proposed three area interconnected-power-system incorporated with a microgrid has been simulated to study the dynamics of frequency deviation and tie-line power deviation due to load changes. For this purpose, a secondary load frequency control method has been adopted. Instead of conventional load frequency strategy, this work is done following the availability-based-tariff for the secondary-frequency-control. Here the frequency-linked-pricing criterion of the conventional power generators due to unscheduled interchange of power is used to determine the generation control error (GCE) which in turn has been minimised through the proper choice of the gains of the proportional-integral (PI) controllers.

The GCE is calculated with the help of two MATLAB Function blocks containing MATLAB scripts and embedded in the Simulink model. One of these two blocks is evaluated using the feedback of the frequency deviation and UI rate published by Government of India. Another block is programmed using the marginal cost functions of the conventional generators described later. The microgrid comprising renewable resources and the storage devices is modelled using individual transfer function blocks of its components and then connected with the grid through the power system transfer function block. This method is also described in the following section. The entire proposed interconnected-power-system incorporated with microgrid is simulated in the MATLAB/Simulink environment to study the effect of connection and disconnection of microgrid on the frequency and the tie-line power dynamics for the load perturbations.

This chapter has explained individually the methodologies adopted for the proposed six cases of the two/three/four area interconnected-power-system with or without renewable energy resources integrated with it. All these case studies are studied under unscheduled interchange price based frequency control under ABT regime. The next chapter describes and analyses the results obtained through simulating the six cases proposed in this chapter. The MATLAB/Simulink has been used for the simulation purpose.

Chapter 5: Results and Discussions

The models of different scenarios for Unscheduled Interchange based Secondary-frequency-control of Renewable Integrated Hybrid Power System under Availability-based-tariff as described in Chapter 3 are solved in this chapter. Results obtained in the MATLAB/Simulink platform are derived and the analyses are made. These results have been presented in a manner that will help to understand different scenarios in a systematic way. The reasons for choosing such interconnected systems either integrating wind power generators or microgrid have been discussed elaborately in Chapter 3.

Case 1 illustrates the thermal-hydro-diesel/biomass based interconnected system working in the ABT scenario. The base load of all the cases considered here is delivered by the thermal generators in multi-area power system. Till date thermal generators are catering largest share of the electricity in India though the renewable shares have already crossed 40% as discussed in chapter 2. The frequency-linked-pricing criterion can be applied for controlling the generation amount as well as the frequency worldwide. These two together can restrict the energy used for the power generation to maintain the grid discipline and hence the cost of generation is reduced. Different countries adopt different frequency-linked pricing criterions. To simulate the cases described in the chapter 3, the UI price table or the characteristics are required. For this purpose, the UI rates imposed by Central Electricity Regulatory Commission (CERC) of India have been used here. Case 2 is the extended for one more area to observe power sharing between the areas for different abnormal situations occurring in the tie-line power. As already mentioned that the RE integration is getting more and more emphasis, the third case has incorporated the wind turbine generator (WTG) in the interconnected-power-system and the effects of its connection/disconnection on the frequency regulation has been investigated. Again the effect of wind power penetration on the output of other generators is observed as they are connected in the interconnected-power-system in the ABT environment so that the results can influence the realistic application of the wind power penetration in Indian context. Similarly the sixth case incorporates the microgrid integration in the interconnected system and its effect on the grid discipline has been studied. Microgrids with renewable energy based distributed generators and the energy storage devices are used for system simulation. The energy storage system can act both as the load and the power suppliers depending on the generation-load balance which in turn can help frequency regulation. All these case studies have used PI controller to mitigate the generation control error (GCE). So particle swarm optimization (PSO) technique has been used to optimize the PI controller parameters. Consequently the system dynamic responses can be improved and settle quickly. The results of these six cases are discussed and analysed one by one in this chapter.

5.1 Case1: Secondary-frequency-control of Three Area Thermal-Hydro-Diesel/Biomass Hybrid Power System based on Unscheduled Interchange (UI) Price

The UI price based interconnected three area hybrid power system having thermal, hydro and diesel generators is shown in Figure 3.1. The coefficients of the transfer functions of the speed governor of thermal, hydro and diesel, the individual turbine blocks and the power system blocks of all three areas are embedded in the block diagrams themselves. The complete block diagram also includes the tie-lines between three areas. Table 5.1 shows the coefficients of the cost functions of different generators and Table 5.2 displays the generator capacity. Here all the thermal generators are assumed to be identical.

Two cases have been observed for load variations in three areas. The frequency, power generation and the tie-line power transient characteristics in all the three areas are studied for load perturbations. Instead of the ACE based conventional secondary control system, UI price based (GCE) secondary control has been adopted here. Therefore the effect on the UI price dynamics is also observed in this study.

5.1.1 Case1.1: Sudden perturbation in the demand in all the power system areas

In this case the demand of 10 MW change in area 1 and 2 each and a demand of 1 MW change in area 3 have been considered. The corresponding transient changes in frequency, tie-line power and UI price dynamics are given in the subsequent Figures in this sub sections.

Table 5.1 Marginal Cost Functions' Coefficients of the Generators [115, 117,118]

a_i (Rs./MWh)	b_i (Rs./MWh^2)	c_i (Rs./MWh)	d_i (Rs./MWh^2)	e_i (Rs./MWh)	f_i (Rs./MWh^2)
40	0.1	38.2	.076	46.6	1.48

Table 5.2 Capacities of the Generators connected in Case 1

Thermal Generator (MW)	*Hydro Generator (MW)*	*Diesel Generator (MW)*
500	500	10

Figure 5.1 shows the frequency characteristics of the three areas during transient conditions. At the steady state condition, the frequencies deviate by 0.2 Hz. The thermal generators of area 1 are scheduled at their full capacities. But the thermal and the hydro generators of area 2 are scheduled at 400 MW. The thermal generator of area 3 is scheduled at 400 MW while the diesel generator is scheduled at its full capacity. Initially, there are overshoots in the frequency characteristics owing to the change of load in all the three areas and the UI price based frequency control strategy reduces the generation control error (GCE) through proper action of the PI controller. This leads to the flattening of the frequency dynamics and the steady state is reached.

Figure 5.2 shows the tie-line power flow between three areas when the load perturbations are activated. The graph shows that the power flows from the first area to the others as the steam generators of area 1 are scheduled at full capacity. The area 2 receive power from area1 through tie-lines when the demand in area 1 and area 2 are changed for 10 MW each and the change in demand of 1 MW is set for area 3. As the change in demand is minimum in the third area, the tie-line power flows from area 3 to the other two areas for the time being.

Figure 5.3 depicts that the UI price of generators of area 1 achieves the steady value of Rs.1613 per MWh. During that instant of time in the frequency characteristic, the frequency is above 50.0 Hz but below 50.3 Hz. As per the CERC regulation the UI price rate is low in that frequency range. Hence the generators are supposed to generate as per the demand only, not beyond than that. Here comes the advantage of price based frequency control strategy. As all the three areas are connected through tie-lines the frequencies of other areas follow the same frequency dynamics that of the first area. Hence they possess the similar UI prices.

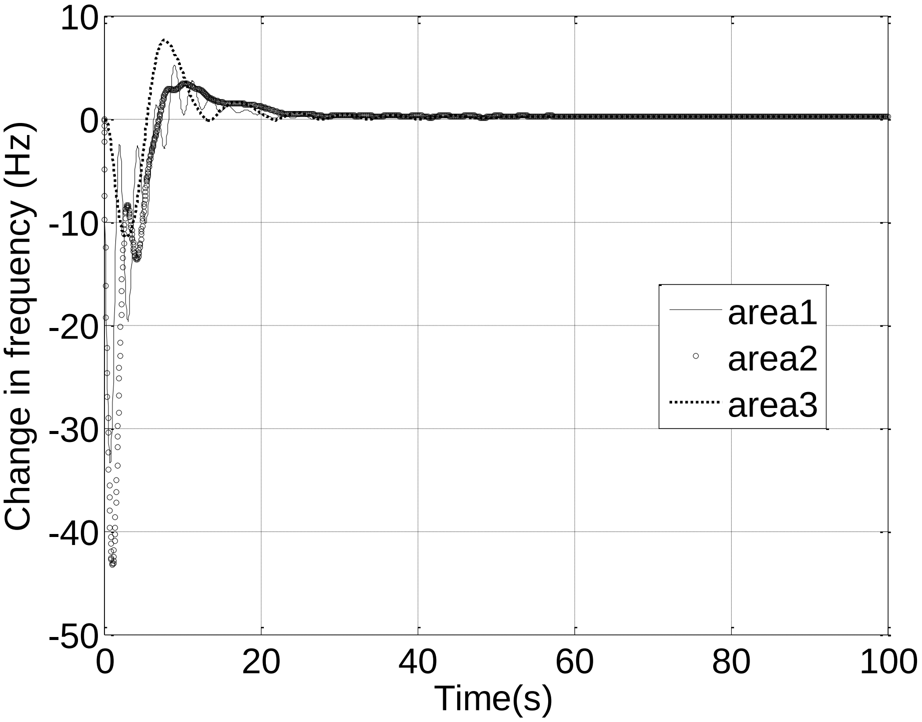

Figure 5.1 Frequency deviations due to sudden change of load in all the power system areas

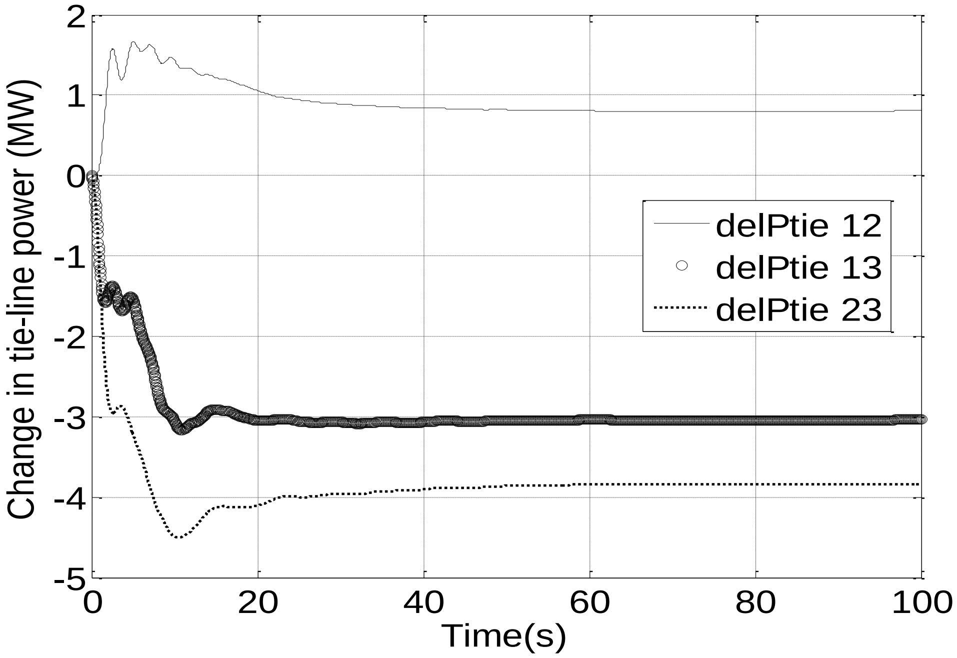

Figure 5.2 Tie-line power deviations due to the changes in load

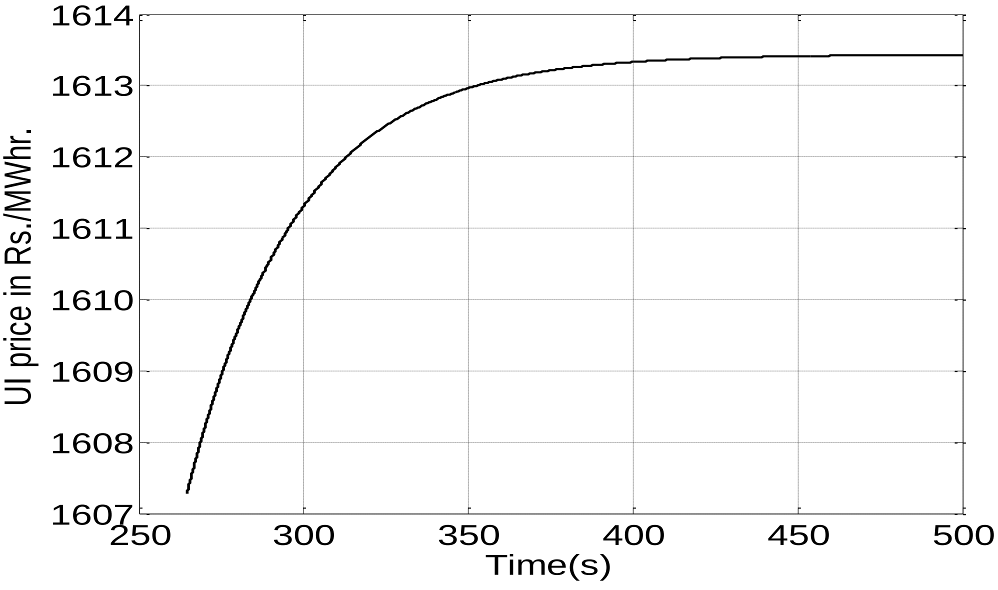

Figure 5.3 The unscheduled interchange price of the generators of area1

characteristics as shown in Figure 5.3. It is observed that the price characteristic takes more time to achieve the steady state value than the frequency and tie-line power characteristics. The UI price lies in the secondary control loop encountering higher time constant. Hence it takes more time to settle.

5.1.2 Case 1.2: Disconnection of the hydel power plant of area 2

A situation may arise when the power generation from the hydel power plant is disrupted due to some adverse weather condition. In that case the hydro power plant is not generating power and the area 2 is now dependent on the thermal generation only. The changes in the demand in all the three areas are same that of the Case 1.1. The sudden load change is mathematically modeled as the step function. The frequency characteristics of all the three areas are depicted in Figure5.4. The primary frequency regulation using speed governor control in each conventional generating unit and the UI price based secondary frequency regulation help the final frequency in all areas to settle near 50 Hz. The proper tuning of the PID controller gains minimizes the GCE derived from the difference of the unscheduled interchange price and the marginal cost of generation in different frequency blocks. The minimized GCE controls the speed governor input as a part of the secondary-frequency-control loop. Thus the final frequency is restored near 50.0 Hz.

Figure5.5 shows that the tie-line power flows from area 1 to area 2. Tie-line power also flows from area 3 to area 2. Both the tie-line power flows have increased compared to Case 1.1. But the tie-line power flow between area 1 and area 3 remains almost same that of the earlier case. The amount of power flow area 1 and area 2 is 2 MW whereas 4.2 MW power flows between area 3 and area 2. This signifies the advantage of interconnection between the power system areas. The renewable power generation is intermittent in nature as these are weather dependent. Hence the disconnection of one of the generators in interconnected-power-system does not disrupt the power flow in that area. The power flow through the tie-lines is revised and maintains the uninterrupted power supply when the power system areas are subjected to sudden change in demands. As the frequency deviates from its nominal value when the generation-demand imbalance occurs in all the areas with hydro generator disconnected, the UI price characteristic also changes following the UI rates (Table 3.1).

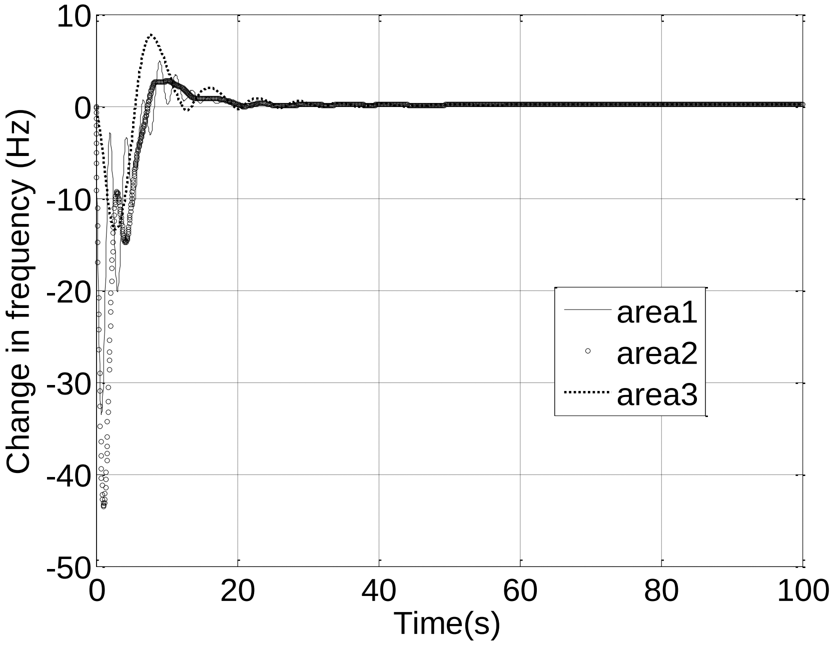

Figure 5.4 Frequency deviation characteristics when the hydro generator is disconnected

A significant effect on unscheduled interchange charge is observed when subjected to a change in the power generation scenario in different generators. Figure5.6 depicts the characteristics of the unscheduled interchange charge of area 1. The UI price is influenced by on frequency deviation from 50.0Hz [3] for different frequency block at different rate. Here the UI charge characteristic trails the same logic. The characteristic shows that the UI price settles at the value of Rs. 1860 per MWHr for the current frequency value. Since the UI rate is higher at this stage, the generators get incentives to escalate the generation level. This surplus generation will improve the total generation which is reduced due to outage of hydro generator. The marginal costs of the generators, which are valued based on their availability, are different from each other.

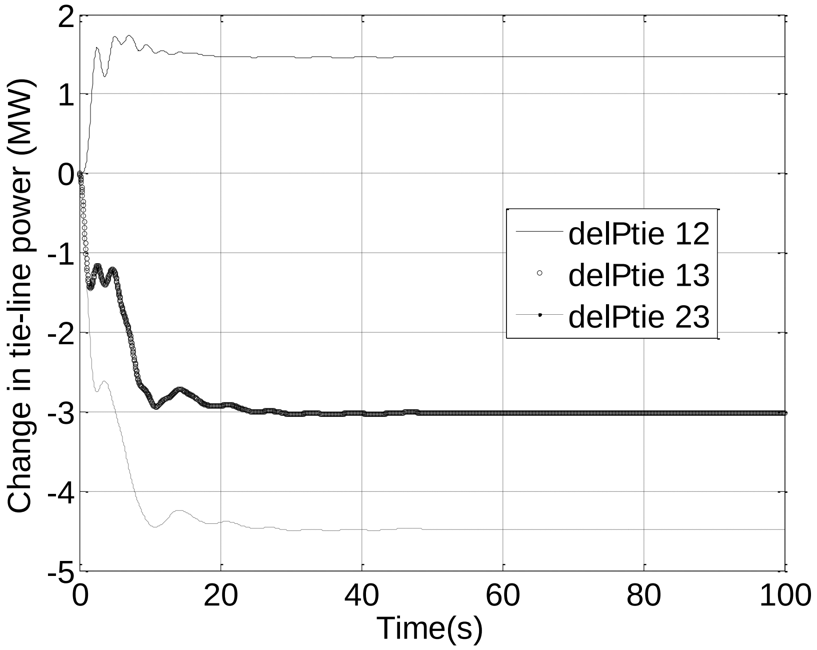

Figure 5.5 Tie-line power deviation with no hydro power output

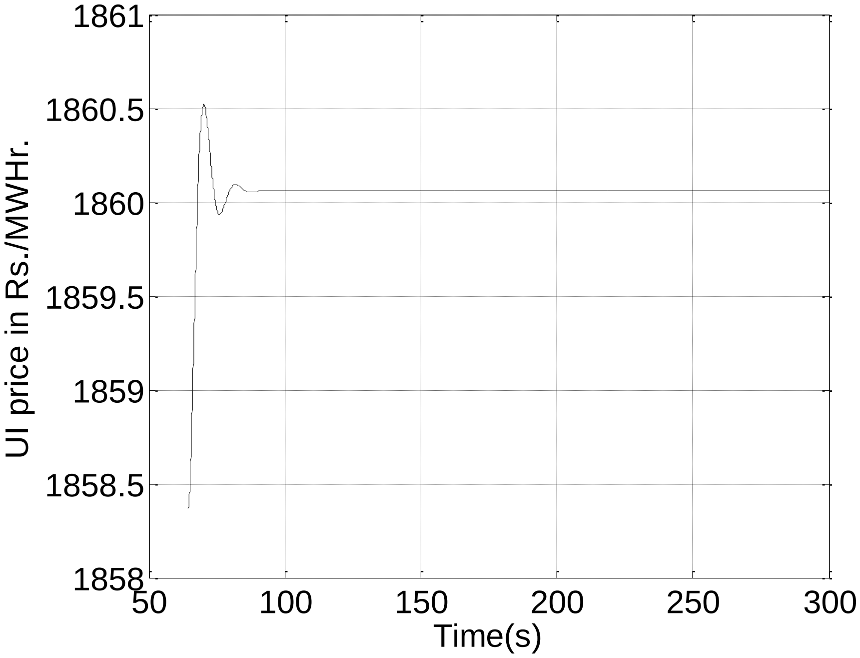

Figure 5.6 UI charge characteristics of area 1 when the hydro power generator is disconnected

The effect of UI price based secondary control on frequency restoration of an interconnected three area power system has been the primary goal of this study. As per the availability-based-tariff (ABT), the generators will receive incentives for generating extra power during peak load hours and the grid frequency is improved. At the same time, the generators will be penalized for generating more power during the lean load period. Hence, no profit can be earned during peak hours without generating more power.

In both the cases, the speed governor based primary-frequency-control of thermal, hydro and diesel generator has been used where the system frequency differs from the nominal frequency when there is sudden load change or there is a speed droop. The use of PI or PID controller in the secondary level control can restore the nominal frequency due to step change in the demand. In the secondary control loop, instead of conventional ACE based control, the unscheduled interchange (UI) based secondary control is used, then it is found that the final frequency slightly differs from the nominal one. It is also observed that more time is required to settle at the steady state value. The UI price based loop offers higher time constant, so the settling time is more. The controller gains are optimized using the inbuilt tuning method of Simulink. The controller parameters can be optimized using any optimization technique which can improve the settling times of the frequency dynamic characteristic, generation deviation and the tie-line power flow changes. In one of the later case studies PSO based optimization technique has been adopted for this purpose. When the interconnected hybrid power system is simulated for generation-load perturbations, the quick settlement of the frequency reduces the net UI charge and the generators have to be paid less for this deviation. Thus the power system operation becomes economic. As the frequency deviation is mitigated quickly, the reliability of the power system operation improves with the proposed scheme of the frequency regulation under ABT era.

In the above discussion the considered system is a very small system incorporating only three power system areas. However if the system becomes bigger, then the effect of different scenarios on the tie-line power has to be understood which is significant for UI based secondary control mechanism. In the following section we concentrate on such slightly bigger system and observe the changes in the tie-line power.

5.2 Case2: Effects of Unscheduled Interchange Price based Secondary-frequency-control on the Tie-line Power Flow in the four area Hybrid Interconnected-Power-System

This case study emphasizes on the effects of UI price on the tie-line power flow when more areas are incorporated compared to the earlier case. The four area interconnected-power-system has been described in section 3.2. Two different situations are studied here. Initially, the frequency and the tie-line power fluctuations are observed for step load perturbations in different areas of the interconnected-power-system under study. The second situation studies the consequences when the tie-line between area1 and other three areas are disconnected.

Table 5.3 Generation Capacities in Case2

Thermal Generator (MW)	Hydro Generator (MW)	Diesel/Biomass Generator (MW)
500	500	10

Table 5.4 Coefficients of the Cost Functions and the Tie-line Power Expression

a_i	b_i	c_i	d_i	e_i	f_i
40	0.1	38.2	.076	46.6	1.48
T_{12},T_{13}, T_{14}, T_{23}, T_{24}, T_{34} = 0.00795					

5.2.1 Case2.1: Sudden changes in the load of all the four power system areas

ABT deals with bulk power. Therefore whenever any load is cut off or is connected to an area the power system dynamics get affected. So such perturbations in the loads are taken into account and the corresponding effects are studied. The effects of sudden changes in demands in four areas considering 5 MW increment in load in area 1 and area 2 each and 0.1 MW increment in load area 3 and area 4 respectively are studied here. Figure5.7 shows the frequency transients in all four areas due to the load perturbations as mentioned above.

Sudden changes in load are mathematically modelled as step functions. Thus step functions create frequency oscillations initially which are reduced gradually with time and the set frequency is recovered. Figure 5.8 shows the tie-line power deviation characteristics. The tie-line power flows there from area 3 and area 4 as the increments in load in area 1 and area 2 have been set at higher values than area 3 and area 4. Area 3 and area 4 satisfy the extra requirement of demand through tie-line in area 2 and area 1. Area 1 and area 2 being at the same capacity, very small amount of power transfer is observed between them. Same thing happens for area 3 and area 4.

Figure 5.8 shows the increment in power generations in all the eight generators connected in the system. The oscillations occurred at the initial stage die out after some time with the help of properly chosen PID controller in the UI price based secondary loop.

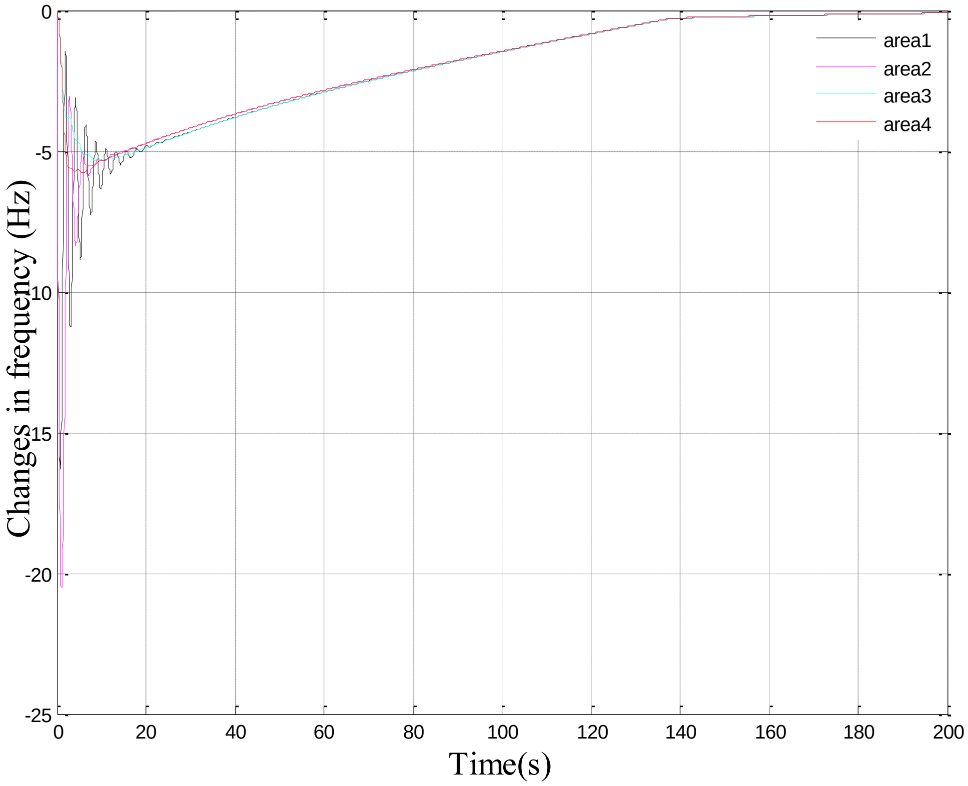

Figure 5.7Frequency deviation (Hz) due to sudden perturbations of load in all areas

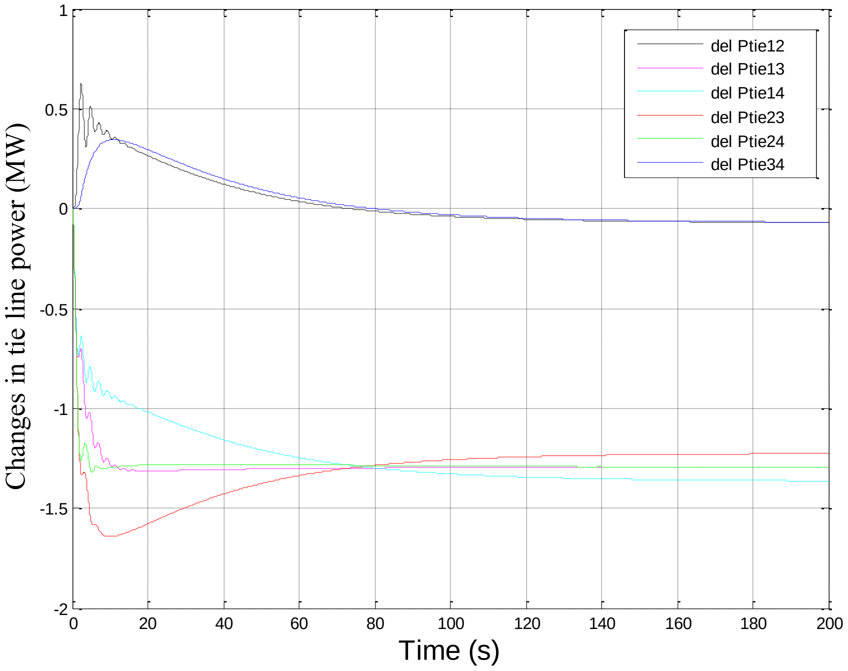

Figure 5.8 Tie-line power deviation (MW) for sudden load changes in all the areas

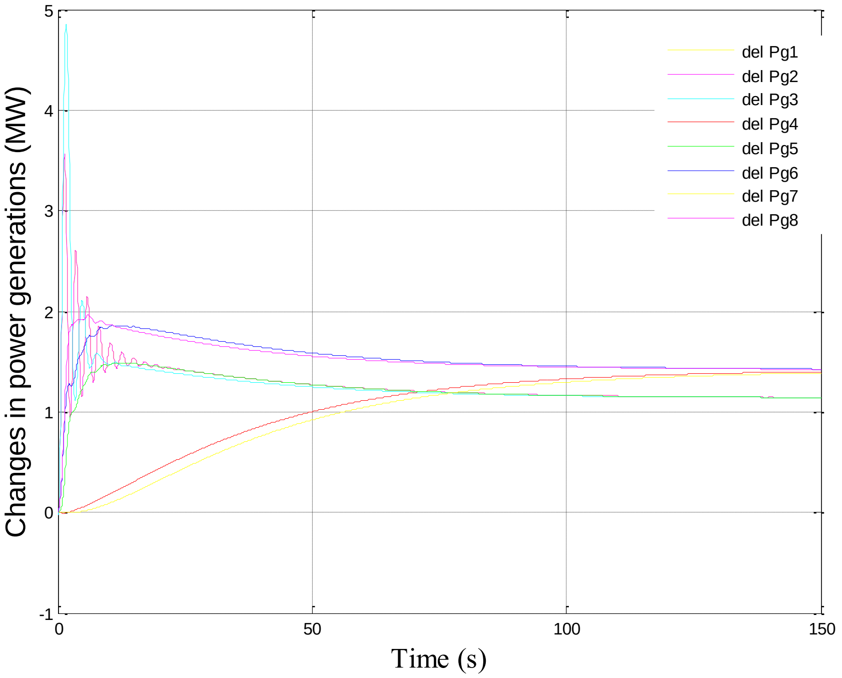

Figure 5.9 Deviations in the generated power from thermal,hydro and diesel/biomass generators for case1

5.2.2 Case2.2: No Tie-line power flow between area1 and other three areas

As the effect of unscheduled interchange based price criterion is being considered here for the frequency regulation study, its effect on the tie-line disconnection has been chosen as another case study where the tie-lines between area1 and other three areas are cut due to some unavoidable consequences. Figure 5.10 depicts the frequency deviation characteristics of all the four areas. After having some overshoots and undershoots, the frequency characteristics of three areas other than the area 1whose tie-line is disconnected from the other three areas, have settled quickly. But, area1 appropriated its settlement at the steady state value around 450 s. This value is quite large compared to the settling times of the other frequency characteristics. The area 1 considers the price based secondary control only for its own generation and no support from the generators of the neighbouring areas. Hence its control loop takes more time to reset its frequency when there is a sudden increment of demand in area 1. As a consequence, the settling time becomes more.

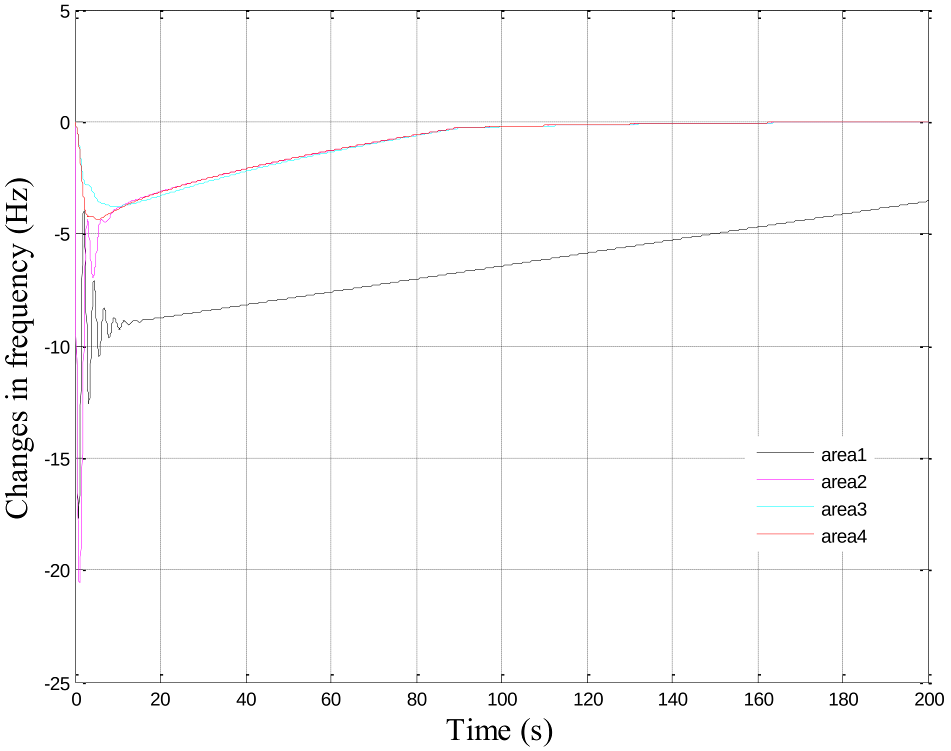

Figure 5.10 Frequency deviation(Hz) characteristics due to sudden changes of load in all areas with no tie-line power flow between area 1 and rest of the power system

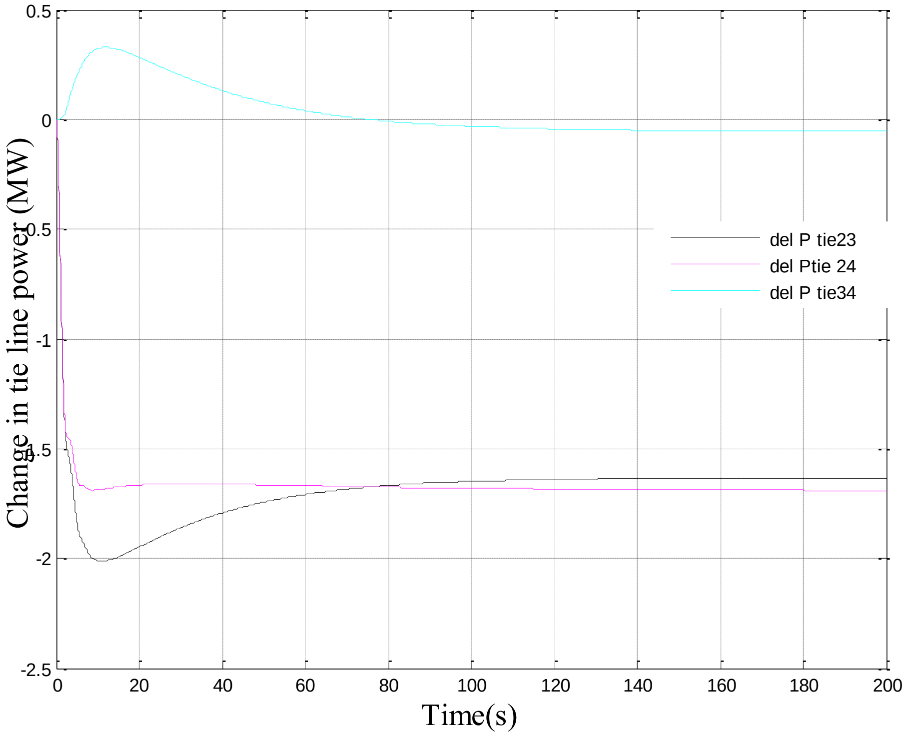

Figure 5.11 Deviations in the tie-line power flow among area 2, area 3 and area 4

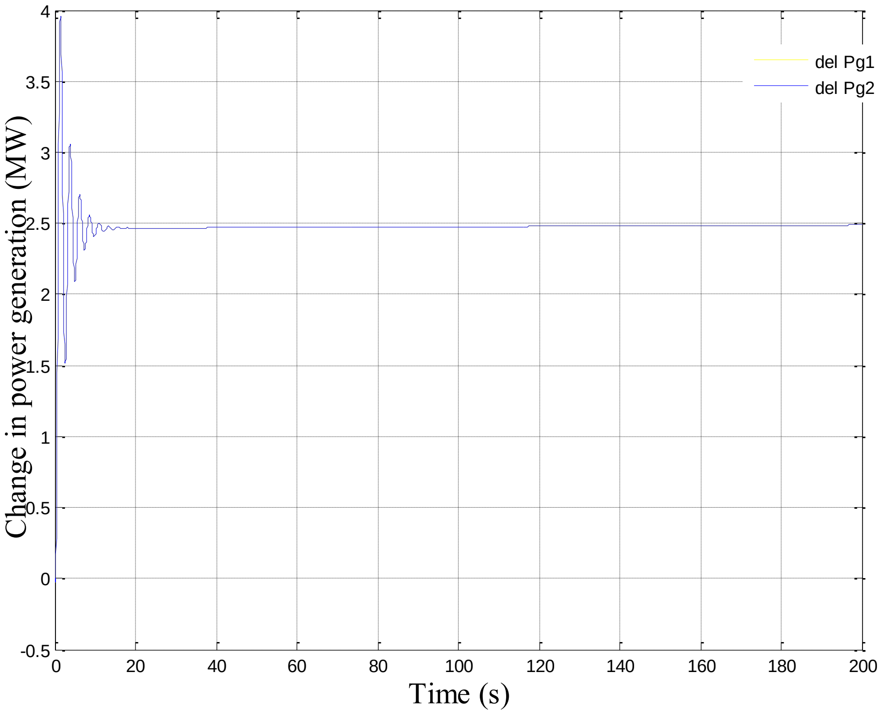

Figure 5.12 Change in the thermal power generation of area1 when tie-lines between area 1 and others are disconnected

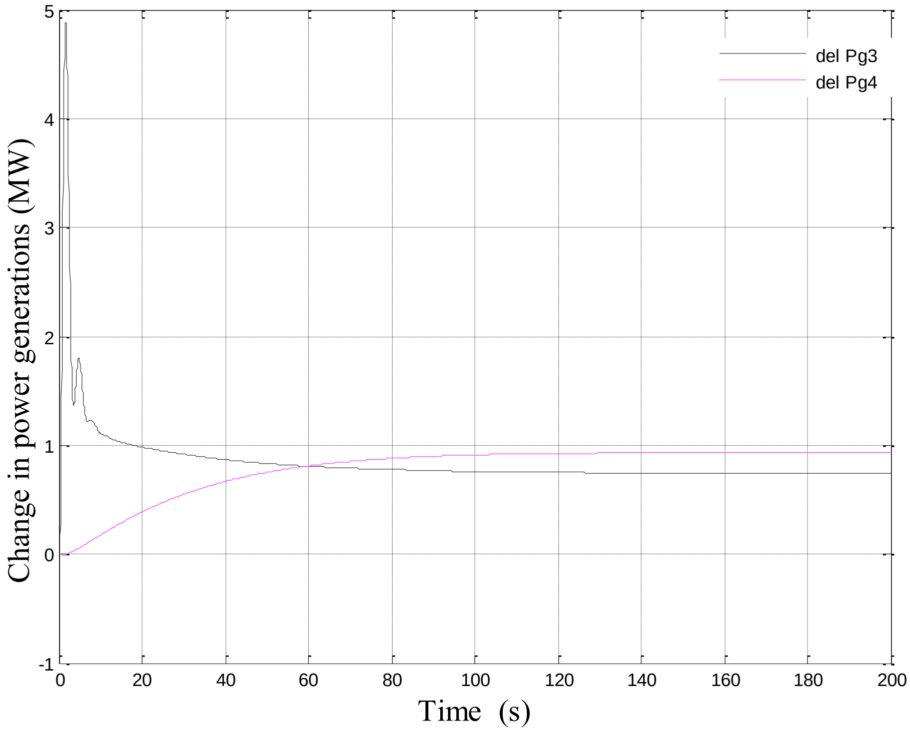

Figure 5.13 Deviation in thermal power generation (*del Pg3*) and hydro power generation (*del Pg4*) of area2 when tie-lines between area 1 and others are disconnected

Figure 5.11 shows the deviations in the tie-line power flow between area 2, area 3 and area 4. The power flow between area 3 and area 4 are trivial but the power flows from area 3 and area 4 to area 2 are not negligible. Area 3 and area 4 share the surplus power of area 2 almost equally.

In Fig 5.12, the deviations in the power generations in the thermal generators of area 1 are shown. Both the thermal generators have shared the increased demand of 5 MW of area 1 equally and received no power through tie-lines as the tie-lines are disconnected. The power generation characteristics of the area 1 and 2 reach steady state vale quickly as these generators compensate the load increment in area 1 internally without the help of tie-line interconnections. Figure 5.13 and Figure 5.14 show the deviations in power generations of thermal and hydro generators of area 2 and deviation in power generations of hydro and diesel/biomass generators in area 3 respectively. In area 2 generators share load equally, but in area 3 the thermal and diesel generators share loads according to their capacities. The Hydro and the Diesel/Biomass generators of area 4 also share the increment in load as per their capacities as shown in Figure 4.15. Hence this study reveals that the interconnections between the power system areas help the areas in allocating excess increased demand through the tie-lines and the system responses get improved.

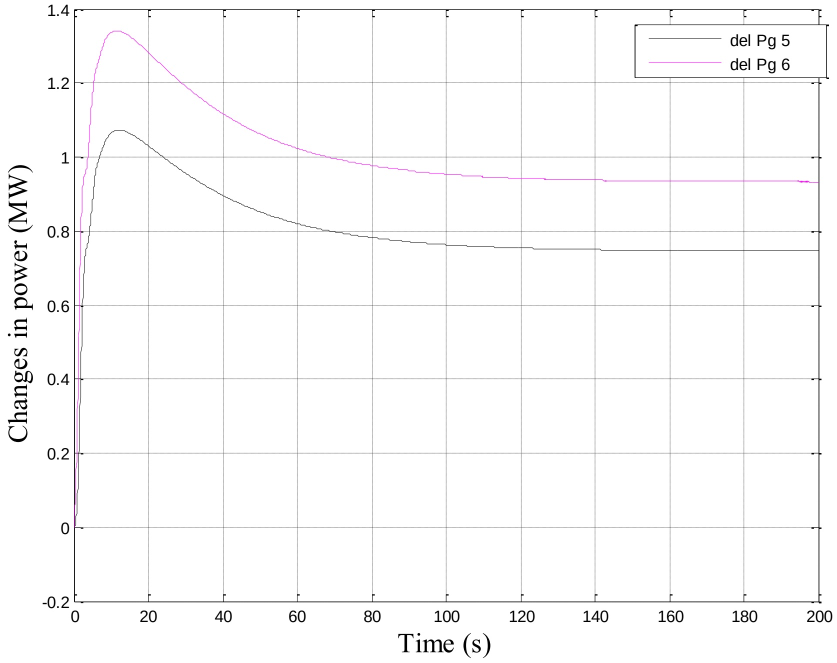

Figure 5.14 Change in thermal power generation (*del Pg5*) and diesel/biomass generation (*del Pg6*) of area 3 with when tie-lines between area 1 and others are disconnected

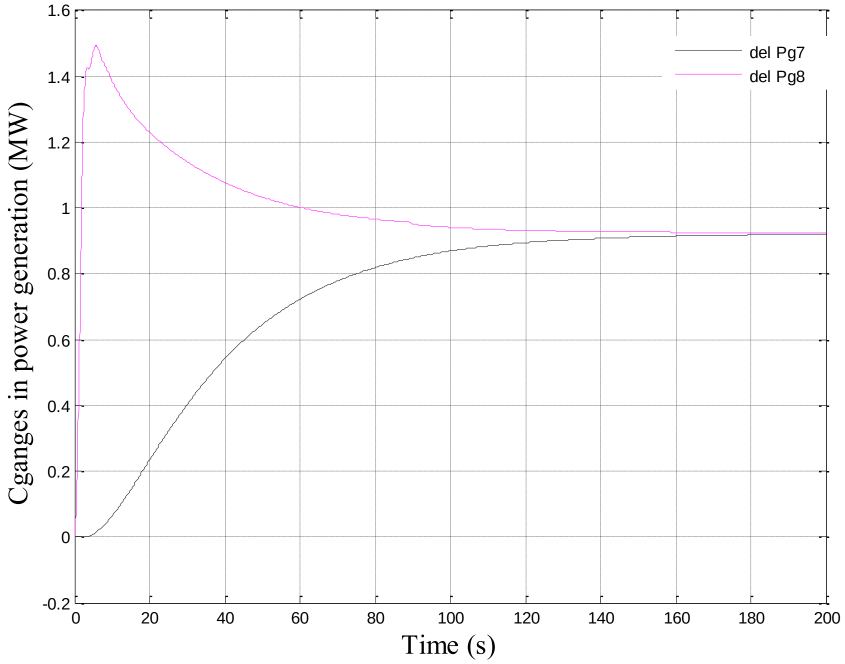

Figure 5.15 Change in hydro generation (*del Pg7*) and diesel/biomass power generation (*del Pg8*) of area 4 when tie-lines between area 1 and others are cut off

5.2.3 Effects of disconnection of the tie-line on the UI rates of the interconnected system

When the four areas of the Thermal-Hydro-Diesel/Biomass based hybrid power system are interconnected through tie-lines, then the UI rates are equal for all areas and settles at the value of 1740 Rs./MWhr. Situation changes when the tie-lines between area 1 and others are cut off. The UI rates are changed in all the four areas. When area 1 is detached from the other three areas, the thermal generators are supposed to supply the increment in demand in area 1 themselves. Hence the generators of area 1 have to increase their generation and as a result the marginal cost is changed. For other interconnected areas the revised UI rates become 1710 Rs./MWhr.

The previous discussions are made concentrating mostly on conventional generators, though in one or two cases biomass generators are conceived with the normal known conventional generators. This may further be understood that all these generators possess characteristics of generation with certainty. However renewable with uncertain nature are these days integrated with the conventional source based power system. In this endeavour we try to observe the power exchanges between the areas. Due to stochasticity of wind input, we cannot schedule its output on prior basis. Hence initially we are keeping wind generator out of the ABT loop. In some parts of India wind input is quite high and it can be used for power generation. So, in the next case study wind generators has been put into the interconnected-power-system along with the thermal, hydro and diesel/biomass generators. In an Indian scenario all these energy input can be made available.

5.3 Case3: Indian Power System with Wind Power Integrated Hybrid Generation under Availability-based-tariff

This investigation includes renewable energy resources along with the conventional energy producers. Thermal-hydro-diesel/biomass-wind based hybrid power generation system has been adopted in this case. The complete block diagram and the corresponding constituents are described in Chapter 3. Area 1 has the steam generators of 200MW capacity and area 3 also has the steam generator of 200MW each whereas steam generator of area 2 has the capacity of 150 MW. These generators cater the base load in all the areas. The hydro generator of area

2 is of 100 MW capacity. A 60 MW wind farm is connected in area1 and a 60 MW dual fuel diesel/biomass generator is connected in area3. The effects of the presence and absence renewable energy based generators i.e. wind, hydro and diesel/biomass generators on the frequency and tie-line power dynamics are studied here. Though the diesel/biomass generator starts with diesel but runs on the biomass derived fuel. The system parameters are shown in Table 5.5. The detailed model of the wind turbine generator has been described in section 3.3. This wind power integrated model of the interconnected three area hybrid power system has been tested for perturbations of demands which is frequently occurring in the power system and the corresponding results are shown subsequently under connection/disconnection of the renewable resource based generators like wind turbine generator, hydro generator etc. The corresponding UI charges are also investigated.

5.3.1 Case3.1:Sudden changes in demands in all areas

Instead of actual values in this case pu values of the generations and load have been used for simplicity of calculation. 0.1pu change in load in area1 and area2 ate considered for this study. In area3 deviations has been caused by 0.04pu load change in area 3. The step functions are to mathematically represent the sudden change in any value. So, step input has been used here to model the sudden increase or decrease in. The speed governor based primary-frequency-controller and the UI price based secondary-frequency-controllers reset the frequency around 50 Hz (5.16). In Indian context, the grid frequency is kept at 50 Hz. Area 1 has the highest overshoot in frequency characteristic compared to the other two areas. The presence of nonlinear pitch control block of wind turbine generator may have caused this overshoot. The entire frequency characteristic takes 15 sec to settle at steady state. Automatic Generation Control (AGC) based secondary-frequency-control system would have settle the characteristic earlier compared to the slower ABT based secondary loop. The choice of controller gains matter here. This might have improved the characteristic with better tuning of controller parameter. Figure 5.17 depicts the tieline power flow between three areas. It is seen that 0.1 pu power flows from area1 to area 2 through tie-line at steady state. The tie-line power of (-0.02) pu flows from area 2 to area3 whereas (-0.08) pu power flows from area1 to area3. The negative sign appears the data which means that the direction of power flow has been reversed. The perturbations in the demand in all the three areas are satisfied through the tie-line flow. All these connection of load or the disconnection of the load happens frequently in the bulk power transfer system.

Table 5.5 Parameters of the Proposed Interconnected-power-system[114, 115,118]

Power System Time Constant each of three areas	T_{p1}, T_{p2}, T_{p3}	20 sec
Power System gains of each three areas	K_{p1}, K_{p2}, K_{p3}	120 Hz/p.u. MW
Steam Turbine Time Constant	T_t	0.3 sec
Speed Governor Time Constant	T_{SG} N_2 N_1	0.2 sec 0.8 0.2
Speed Regulation of the Governor	R	3.03Hz/p.u. MW
Hydro Turbine Transfer Function Model	T_{SGH} K_{SGH}	48.7 sec 1
	T_{HA}	10 sec
	T_r	0.513 sec
	T_w	1 sec
Tieline Time Constant	$2*pi*a_{12}*T_{12}(where T_{12}=T_{23}=T_{13})$	0.05 sec
Diesel Engine regulator time Constants	T_{d1}	0.2sec
	T_{d2}	0.1 sec
	T_{d3}	0.002 sec
Diesel Engine regulator gain	K_d	1
Diesel Engine actuator time constant	T_{D4}	.24 sec
Wind Generator primary-frequency-control parameters	T_r	0.1 sec
	T_w	6 sec
	R	2.4
Wind Generator inertia control parameters	K_i *(gain of integral controller)* K_P*(gain of proportional controller)* T_a*(turbine time constant)* *H (equivalent inertia)*	1.58 1 0.2 sec 3.5MW-s/MVA
Coefficients of marginal cost Functions	a_i*(Rs./M Wh)*	40
	b_i *(Rs./M Wh^2)*	0.1

	c_i(Rs./M Wh)	38.2
	d_i(Rs./M Wh^2)	.076
	e_i(Rs./M Wh)	46.6
	f_i(Rs./M Wh^2)	1.48

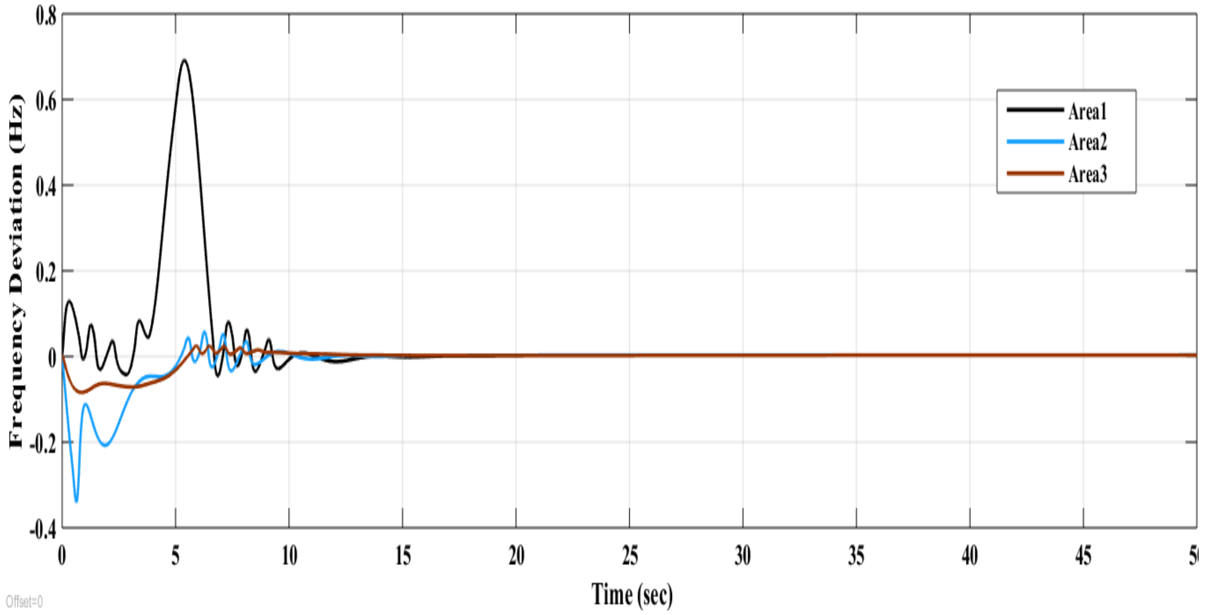

Figure5.16 Change in frequency characteristic

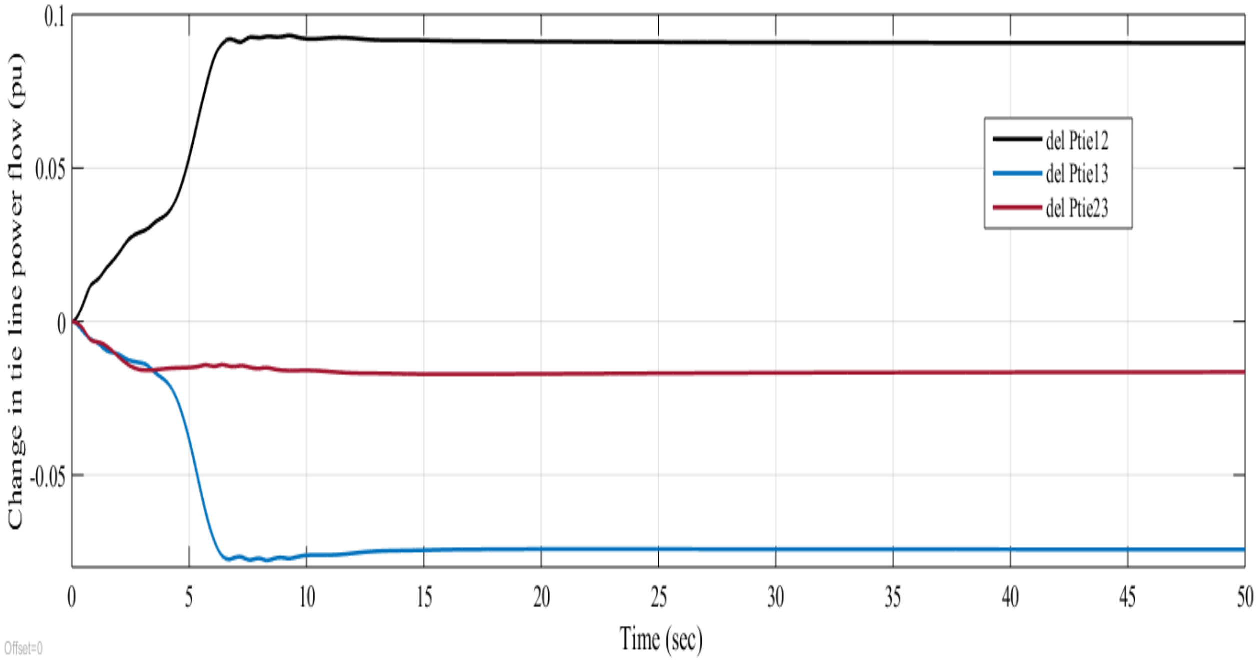

Figure 5.17 Characteristic of the tieline power deviation subject to the sudden change in demands

5.3.2 Case3.2: Sudden changes in demands in all areas with wind generator disconnected

For sustainable power generation green energy sources are being focused majorly in today's power producing system. Paradigm has been shifted towards the renewable energy resources like wind, solar, biomass, tidal power etc. Therefore integration of wind power in the proposed hybrid power system has been studied here. Certain adverse atmospheric conditions like gusty wind or very low wind etc affect the wind turbines operation and these are needed to be disconnected from the grid for the time being. In that situation the study of the stability of the interconnected-power-system in terms of frequency is observed here.

To model this situation the wind generator is disconnected by removing the wind generator transfer function block from area 1. Figure 5.18 illustrations the frequency deviations in all the three areas when subjected to same change in load like the earlier one. In this case the peak overshoot of the frequency characteristic of area1 has been reduced. The wind energy conversion system (WECS) has no contribution to the grid inertia. Therefore, the inertial control is provided through emulating inertia. This model of the wind turbine generator has been described in section 3.3. Considering this idea, the WECS model is adopted here and it contributes to the grid inertia. In this case study as we are disconnecting the wind model, the emulating inertia is also considered to be absent in the complete block diagram. The characteristic shows that the system frequency does not attain steady set frequency and shows 0.01 Hz frequency deviation. Therefore the cutting off of wind turbine generator affects the adversely the frequency regulation of the proposed system. At the same time, as the wind turbine generator blocks are absent, the overshoot of the frequency characteristic is reduced. Now area 1 and 2 have almost equal peak overshoot but, these are marginally higher than that of area 3. The presence of diesel/biomass generator in an area can make the system better in terms of the frequency stability compared to other areas. When the wind generator is disconnected, the frequency characteristics of all the areas take more time to settle at steady state. The emulating inertia provided by the wind turbine generator model contribute to the grid inertia and hence the overall time constant improves.

Figure 5.19 shows the deviations of the tieline power between three areas. The tieline power flows from area2 to area1 and area3. Small amount of power flows from area 3 to area 1. As the wind turbine generator is cut off from area 1, the capacity of area1 is reduced. Therefore the change in demand in that area is catered by the other areas through tie-line. Hence the adjustment due to the increment in load in all areas is accomplished through the change in the direction of tieline power flow between the areas.

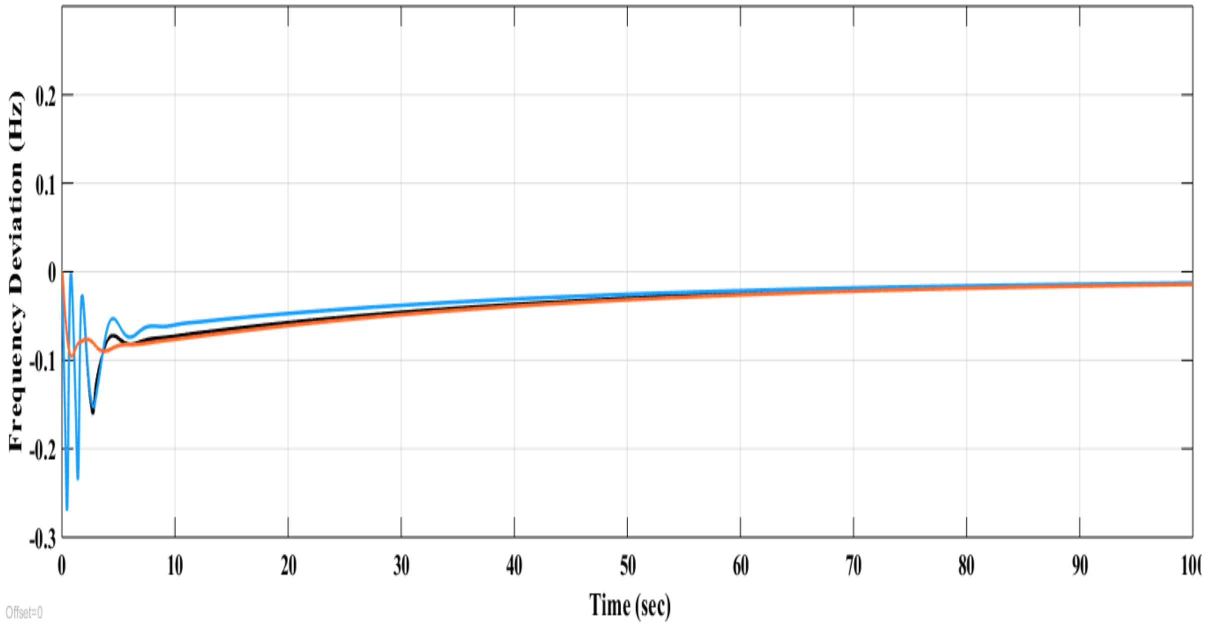

Figure 5.18 Deviation in frequency characteristic with no power out put from the wind generator

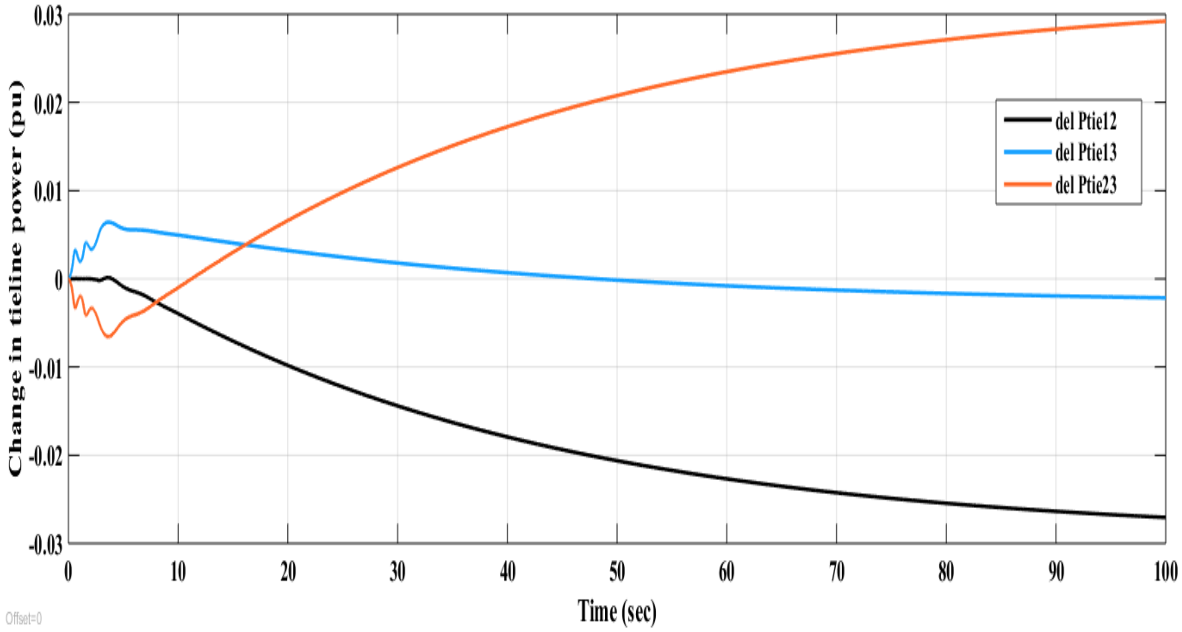

Figure 5.19 Characteristic of the deviation in the tieline power due to sudden perturbation in load without the wind power output

5.3.3 Case3.3: Sudden change in demand in all areas with hydro generator disconnected

Power generation in a hydel plant based on run of river plant depends on the discharge of water. To supply the base load of an area from a hydro power plant the acceptable flow of water is always required to be maintained. In this part of study, the shortage of water supply forces the hydro generator of area 2 is to stop power generation and it is disconnected from the other generators. In this situation the load used to supply by the hydro generator earlier, is to be catered by the generators connected in the other two areas through tie-line. The corresponding frequency deviation characteristic is depicted in Figure 5.20. This frequency deviation characteristic resembles similar pattern that the first case settles around 15.0 sec at the nominal value. In subsections 5.3.1 and 5.3.3 the wind turbine generator is present in the complete block diagram and it introduces overshoots in the frequency characteristic during transient condition.

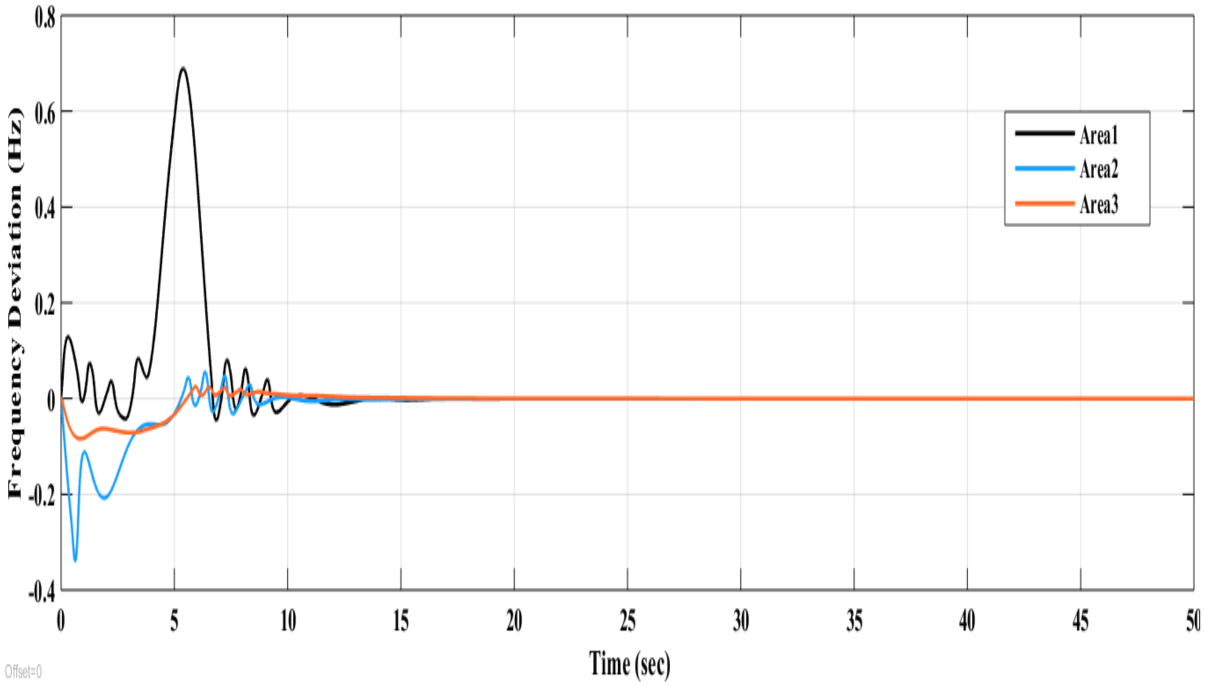

Figure 5.20 Deviation in the frequency characteristic with no hydro generator output

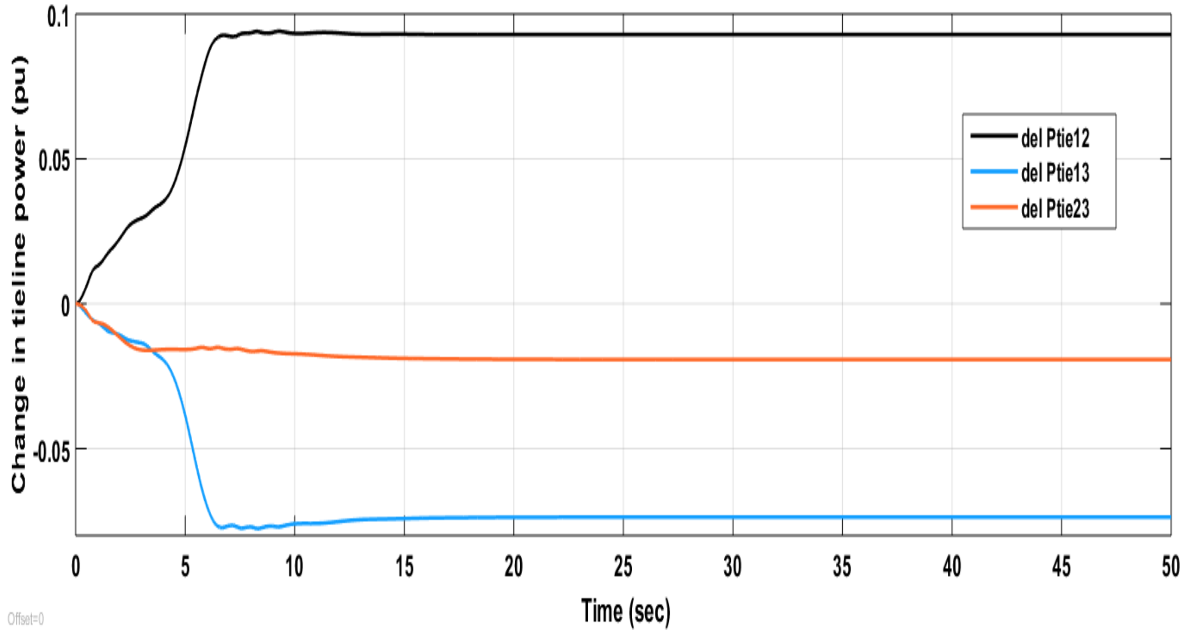

Figure 5.21 Characteristic of the tieline power when the hydro power generator is disconnected

When the hydro generator is not connected in area 2, the changes in tie-line power between the areas are shown in Figure 5.21. These plants are disconnected from the hybrid power generation system during the high flood condition or low run off situations. In this situation, the base load is catered by the thermal generators and the peak demand is supplied from two areas through the tie-line power. As the capacity of the area 2 has decreased owing to the disconnection of the hydro generator and the load has increased simultaneously, the tie-line power flow of 0.1 pu from area 1 to area 2 has increased to accommodate the increment of demand in area 2. It is also observed that the power flow from area 3 to area 2 has been amplified to compensate the load not supplied by the hydro generator as the hydro generator is disconnected. Thus the load of area 2 is being supplied from the other generators.

5.3.4 Case3.4: Sudden changes in demands in all areas with diesel/biomass generator disconnected

Figure 5.22 shows the system frequency characteristic when the biomass generator is disconnected from area3. The dual fuel diesel/biomass generator is used to cater the peak load. The diesel/biomass generator works on the governor control as it does not support automatic speed control. A third order open loop transfer function is used to model the diesel engine generator for primary governor based speed control. In contrary the thermal generator uses the second order open loop transfer function. Therefore the sudden change of demand which is modeled as step function influences the dynamics of the thermal generator more compared to that of the diesel/biomass generator. Hence the removal of the diesel/biomass generator impacts the peak overshoot in frequency characteristic as depicted in Figure5.22 trivially. The settling time remains the same that of the case described in 5.3.1. It may be inferred that the thermal generator dynamics pre-dominates the time response in the present UI price based frequency regulation characteristic due to its higher capacity.

In this case, the power flow from area1 to area 2 has been increased compared to case depicted in Figure5.23. As one of the generators of area 3 is disconnected, the power flow from area 3 to area 2 and to area 1 has decreased. The impact of the absence of the diesel/biomass generator does not affect the frequency and tieline power characteristics significantly as it is supplying the peak load.

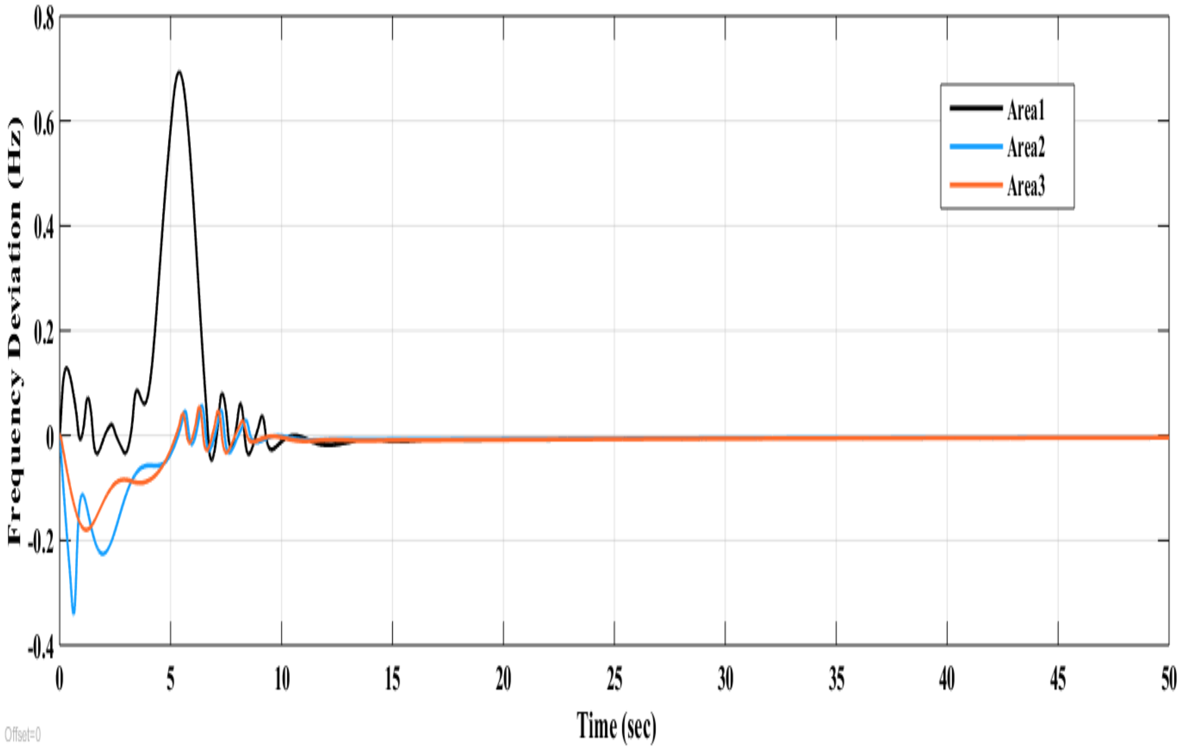

Figure 5.22 Deviation in frequency characteristic with no power output from the diesel/biomass generator

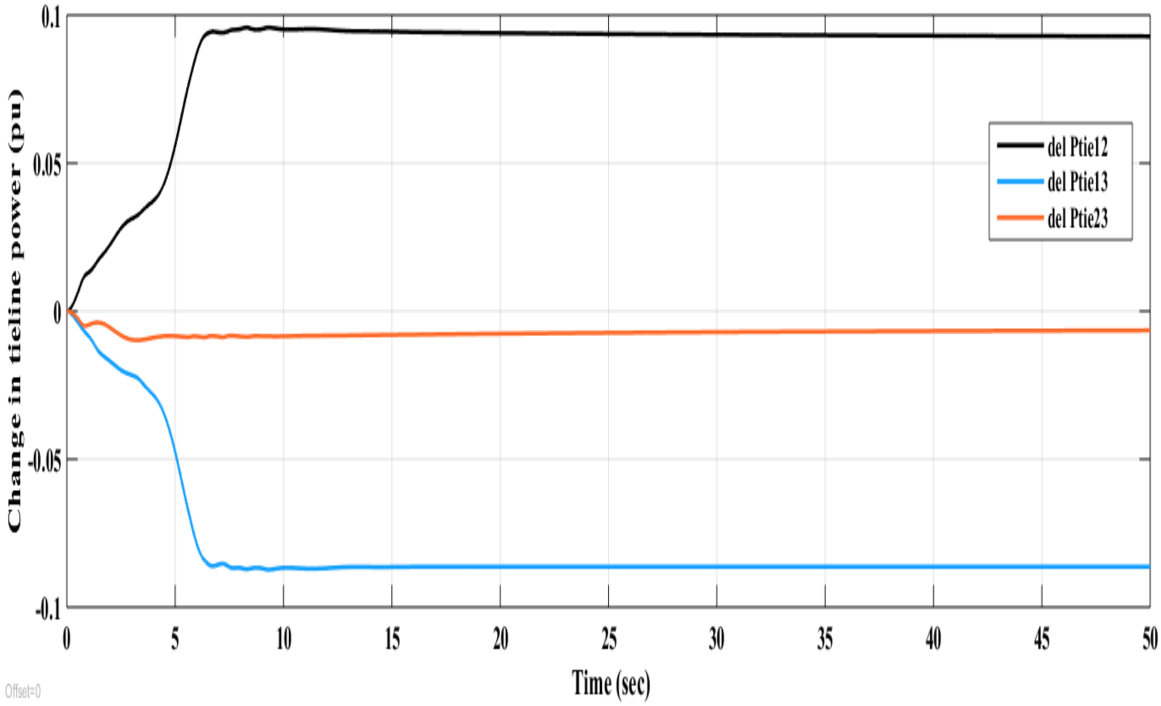

Figure 5.23 Characteristic of the tieline power deviation due to sudden perturbations in demands in absence of the diesel/biomass generator

5.3.5 Effects on Unscheduled Interchange price

In the availability-based-tariff (ABT) regime, the unscheduled interchange mechanism is used to achieve the grid discipline in terms of frequency. Hence this work has chosen the UI price based secondary-frequency-control of thermal, hydro, wind and diesel/biomass power generation system. For the sake this application the availability of generated power from different generators are need to be used. At the same time the marginal cost and the cost due to frequency deviation in the interconnected areas are also evaluated. Therefore the certainties in the available power from different generators are important. As the wind power is intermittent in nature, its availability is uncertain. Therefore the wind power generation is kept out of the UI based secondary-frequency-control loop. The unscheduled interchange prices for three areas are now calculated using the deviation of the actual generation of the steam, hydro and diesel/biomass generators from scheduled one. The deviation of the grid frequency during the transient situations is also observed and the corresponding UI prices are also calculated. As the frequency dynamics are settled nearly at 50 Hz, the steady state values of the UI prices remain the same around 200 Rs./MWhr. According to the Deviation Settlement Mechanism (DSM) vector published by CERC in 2014 [23], the UI rates remain within 1780 Rs./MWhr and 0 Rs./MWhr for frequency range between 50.03 Hz to 50.00 Hz. The UI prices achieved here lies within this limit. Therefore, the integration of renewable energy based power generating unit with the conventional generators in an interconnected-power-system can be studied for frequency regulation along with the support of economic power generation in the availability-based-tariff (ABT) regime. This next case is also tested for the changes of demand in the two area interconnected-power-system under ABT regime. The main objective of this case study is to apply the PSO optimized PI controller parameters to investigate its effect on the system dynamic responses subjected to the step load change with 250 and 500 iterations respectively.

5.4 Case4: Effects of Particle Swarm Optimization (PSO) with Time-Varying Acceleration Coefficients on Renewable Integrated Two Area Load Frequency Control under ABT

To get better stability response of the frequency characteristics as obtained earlier, optimization of the PI controller is found necessary. An algorithm has been proposed for this purpose in the two area thermal-wind-hydro power based interconnected-power-system operating under availability-based-tariff (ABT). The frequency and tieline power dynamic response due to change in load has been studied here. To check the effects of the optimized PI controller on the UI price based secondary frequency response, Particle swarm Optimization (PSO) criterion has been used here. The details of the PSO based modelling has been described in section 3.4. The research methodology describing the algorithm has been enumerated in the section 4.4.

Area 1 has one thermal generator and one wind generator whereas area 2 comprises one thermal generator and one hydro generator. This combination has been chosen considering the Indian power system scenario [37]. The conventional generators like thermal and hydro generators are considered to operate under ABT regime but the wind turbine generator having stochastic input is kept out of the ABT loop. The later one is operating only on the primary-frequency-control strategy. The proposed system has been already described in chapter 3. The thermal generator in area 1 has 200 MW rating and the wind turbine generator is of

60MW capacity. A 150 MW thermal generator and 100 MW hydro turbine generator are supplying the second area. The system parameters are presented in Table 5.4.

The proposed two area interconnected hybrid power system is subjected to the sudden change in load and the corresponding system dynamics are studied. 10 MW load has been decreased in Area 1 and area 2. The proposed system is studied for frequency regulation without using the PSO based optimization criterion. The PI controller gains are chosen iteratively in the first case. The Particle Swarm Optimization Technique with Time Varying Acceleration Coefficients has been applied to optimize the PI controller gains. Like the previous. The frequency deviation and the tieline power deviation are examined. The effect of the PSO based optimization is also observed on the reduction of the Generation Control Error (GCE).

Table 5.6 Parameters of the Generators and the Power System Areas connected in the proposed System

Generator	*Parameters*	Values
Thermal	*Speed Regulation of the Governor*	3
	Gain of Speed Governor	1
	Time Constant of Speed Governor	0.3 s
	Generator Dead Band Parameters N1, N2	0.8, -0.2
Hydro	*Speed Governor Time Constant*	48.7s
	Hydraulic Amplifier Time Constant	10 s
	Decay Time Constant of Dash Pot	0.5 s
	Water Starting Time	1 s
Wind	*Ishout filter Time constant*	6 s
	Frequency Transducer Time Constant	0.1 s
	Controlled WECS Gain and Time Constant	3.5 and 0.2 s
	Speed Regulator Proportional Constant	1.5
	Speed Regulator Integral Constant	0.15 s
PowerSystem	*Gain*	120
	Time Constant	20s

5.4.1 Case 4.1: Study of the Dynamic Response of the Proposed system without the Application of PSO

The proposed two area thermal-hydro-wind power based interconnected-power-system has been subjected to the sudden load change. Similar to the earlier three cases the thermal and hydro generators operates in the secondary-frequency-control loop under ABT regime. But, the wind speed being intermittent in nature, the control of wind turbine generator (WTG) is kept outside the UI price based secondary-frequency-control loop. This case has been studied for the constant wind speed when the wind turbine generator is integrated in the power system area 1.

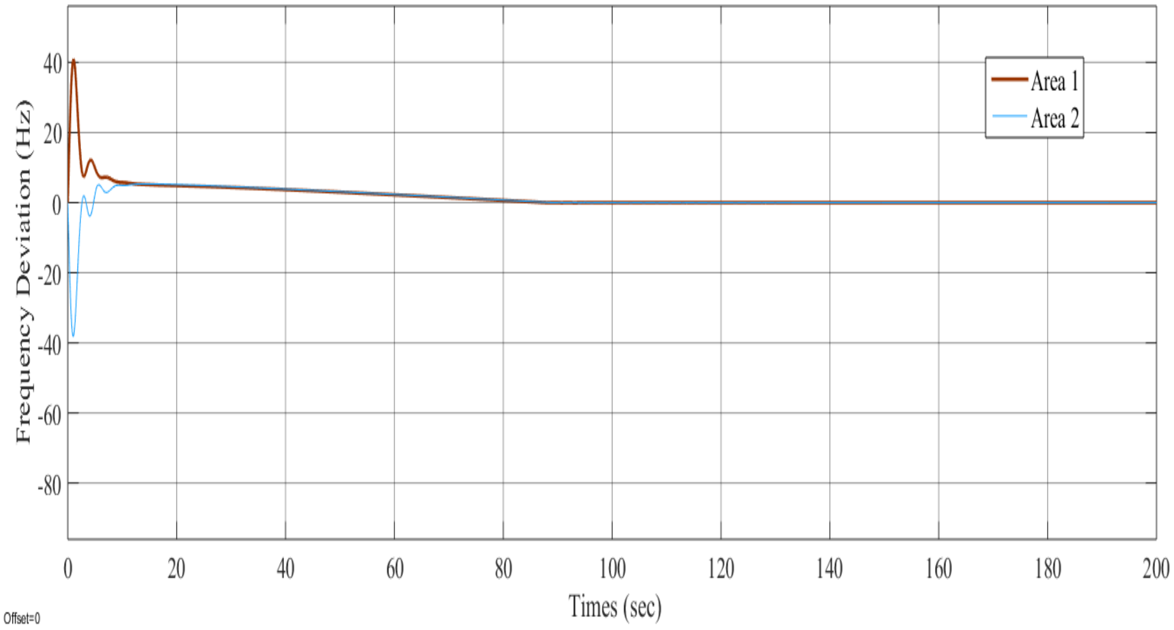

Figure 5.24 Frequency Deviation Characteristic without the application of PSO

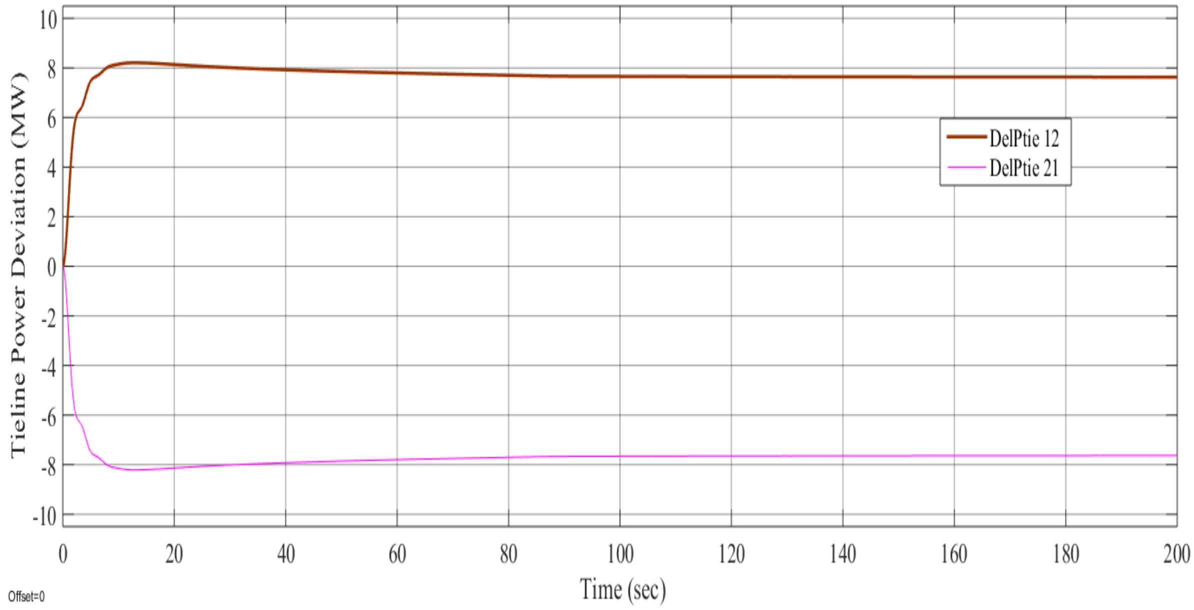

Figure 5.25 Characteristics of the Tieline power Deviation without the application of PSO

The frequency characteristic settles at around 80 sec which is quite high as shown in Figure 5.24. The reason may be described as the introduction of the unscheduled interchange (UI) based pricing method in the feedback path of the proposed system. If the PI controller gains are chosen through optimization then better results could have been obtained. With the knowledge that the improvement can be done in the system dynamics through the application of optimized PI controller gains, the attempt of PSO based optimization of controller gains has been tried. With this application, quicker system response would have been attained. Hence the next case study is done with optimized PI gains.

In the first step, the two area power system has been simulated without the PSO application. Figure 5.25 shows the deviation of the tie-line power flow between the two areas. Some 7.625 MW power flows between the areas which are equal and opposite. Figure 5.26 characterise the deviations in generator power and the characteristics settle around 80 sec. The changes in the demands in the areas are accommodated by the changes in the generated power. In area 1 thermal generator has decreased the generation by -2.375 MW where in area 2 thermal generator 2 has increased 0.455 MW generation and the hydro generator has increased 1.915 MW power generation. WTG output remains unaltered as the wind speed remains constant. Therefore, total change in the generated power and the tie-line power is adjusted by the wind power. The tie-line power changes are (-2.375) MW, (-7.625) MW and

(-10) MW in area1. Similarly, in the area 2 the change in the generated power of (+2.375) MW, change in tieline power *DelPtie* of (+7.625) MW and load of change (-10) MW are balanced at the steady state condition.

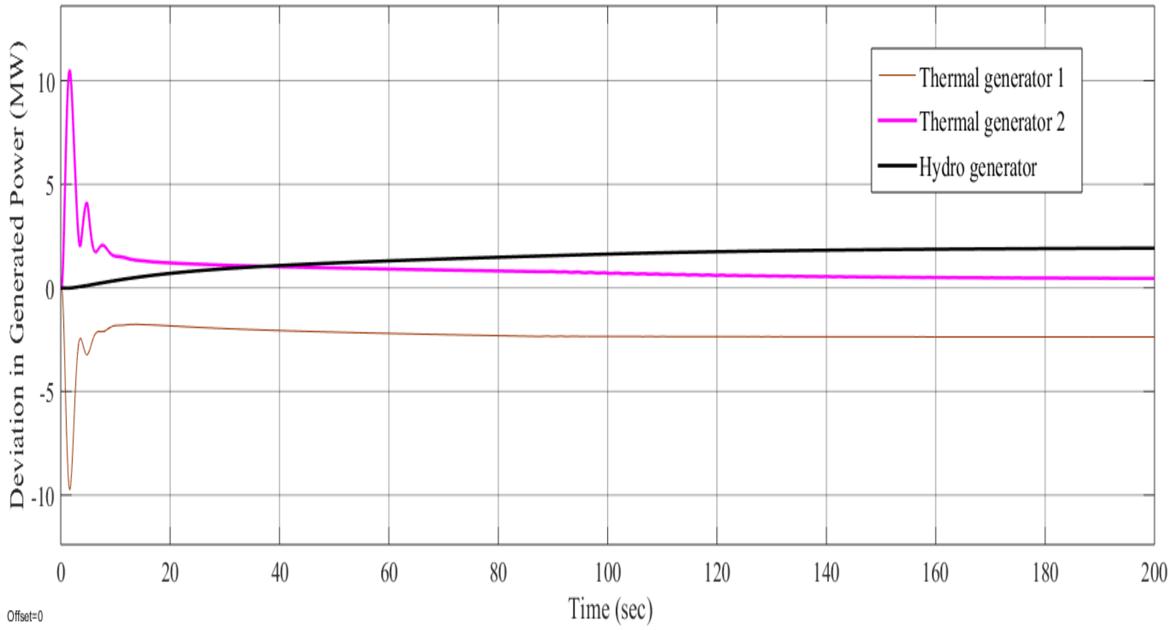

Figure5.26 Characteristics of the deviation in the Tieline Power (MW) flow without PSO

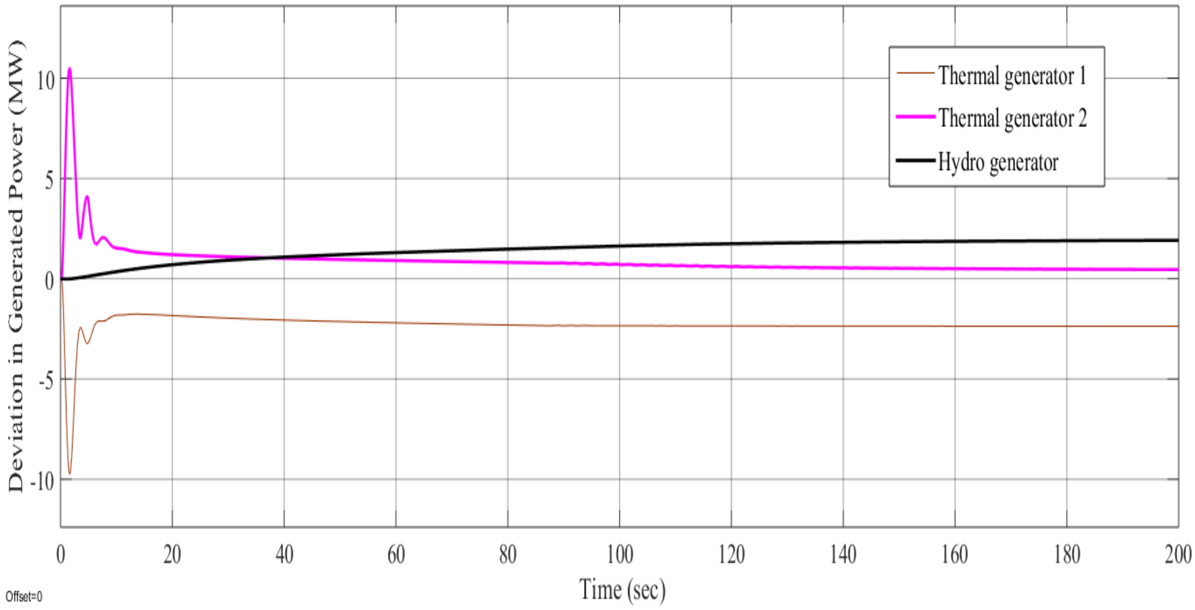

Figure 5.27 Characteristics of the Generated Power (MW) Deviations without PSO

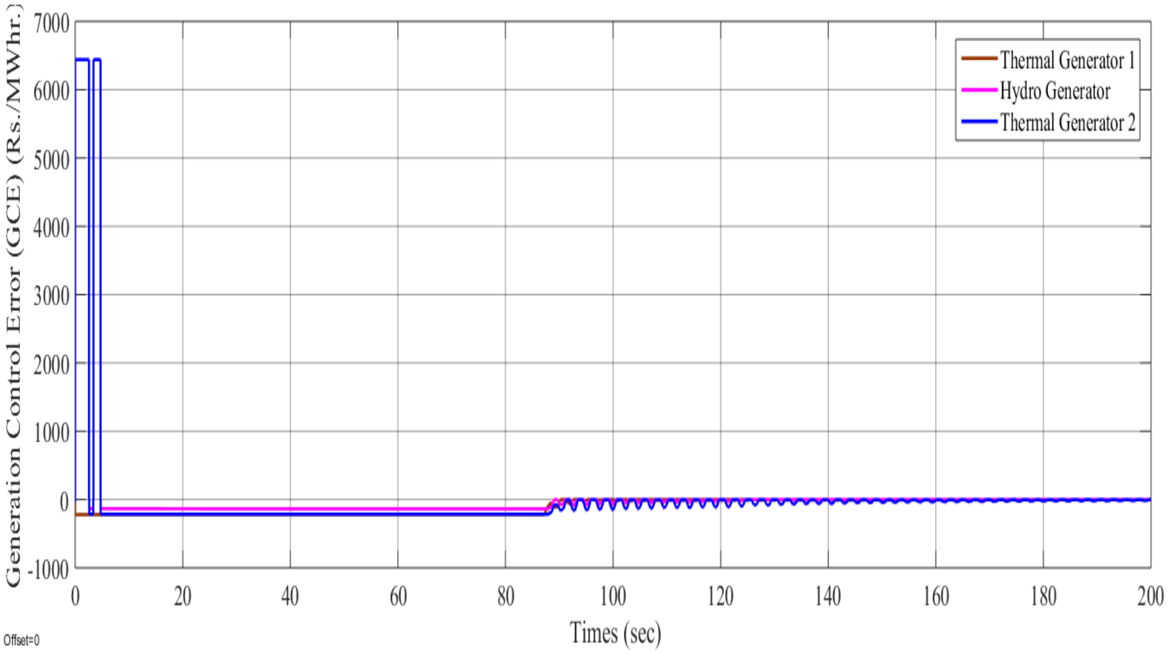

Figure 5.28 Generation control Error (GCE) Characteristics without the application of PSO

The generation control error (GCE) characteristic as shown in Figure 5.28 settles around 90 sec. Whether the generator will receive the incentives or will be penalised, that depends on this characteristic. As soon as this characteristic settles at the steady state, the GCE in Rs./MWhr is decreased and the power system frequency attains the nominal grid frequency. Thus the grid discipline is established. Hence, particle swarm optimization (PSO) technique with time varying acceleration coefficients has been chosen for optimising the controller gains. The next case studies the dynamic responses for the proposed system with PSO optimized PI controller parameters.

5.4.2 Case4.2: Dynamic Response of the Proposed Interconnected Two Area Power system Optimized with PSO having Time Varying Acceleration Coefficient (TVAC)

As mentioned in the preceding section that the frequency response take more time to get steady, PSO based optimization criterion has been used here. Particle Swarm Optimization technique has been applied to optimize the PI controller gains in this thesis. 250 iterations and 500 iterations have been applied. Two iterations can make differences in the settling time. 500 iterations can take more computational time but it gives better convergence. The detailed technique as applied here has been described in the previous chapter. The optimized values of the PI controller gains are displayed in Table 2. Figure 5.29 shows the frequency deviation characteristic for 250 iterations and Figure 5.31 depicts the same for 500 iterations. The frequency characteristics using the optimized controller gains with the help of modified PSO program settle very fast. Thus it can be inferred that the properly optimised PI gains can make the system dynamic response much better when subjected to the change in demand. The modified PSO based the Best Cost convergence characteristics are shown in Figure 5.31 and Figure 5.32. The graph shows that convergence characteristic falls steeply after 250 iterations and the characteristic converges at a much lower value.

Table 5.7 The values of the PSO optimized Proportional (K_P) and Integral (K_I) Constants for Two Thermal Generators and One Hydro Generator

Generator	Proportional Constant (K_P)		Integral Constant (K_I)	
	250 iterations	500 iterations	250 iterations	500 iterations
Thermal Generator1	0.0001134	-0.000154	0.0006766	0.00011016
Thermal Generator 2	0.000147	3.32993e-05	7.959605e-05	1.6281716e-05
Hydro generator	-0.000666	-0.0010556	-4.775789e-07	-7.57539e-06

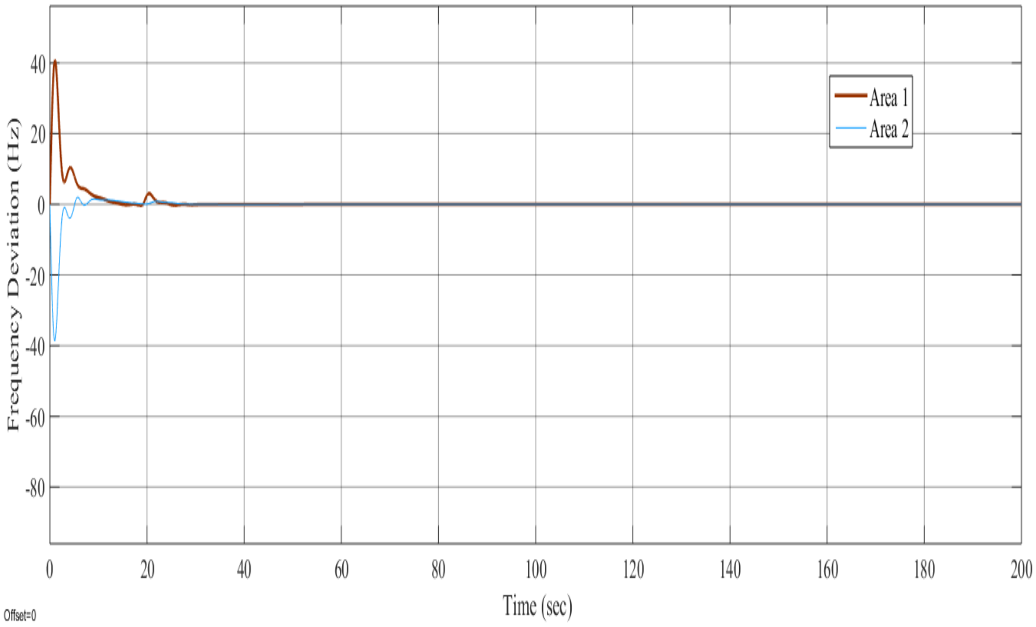

Figure 5.29 Frequency Deviation Characteristic with the application of PSO (TVAC) for 250 iterations

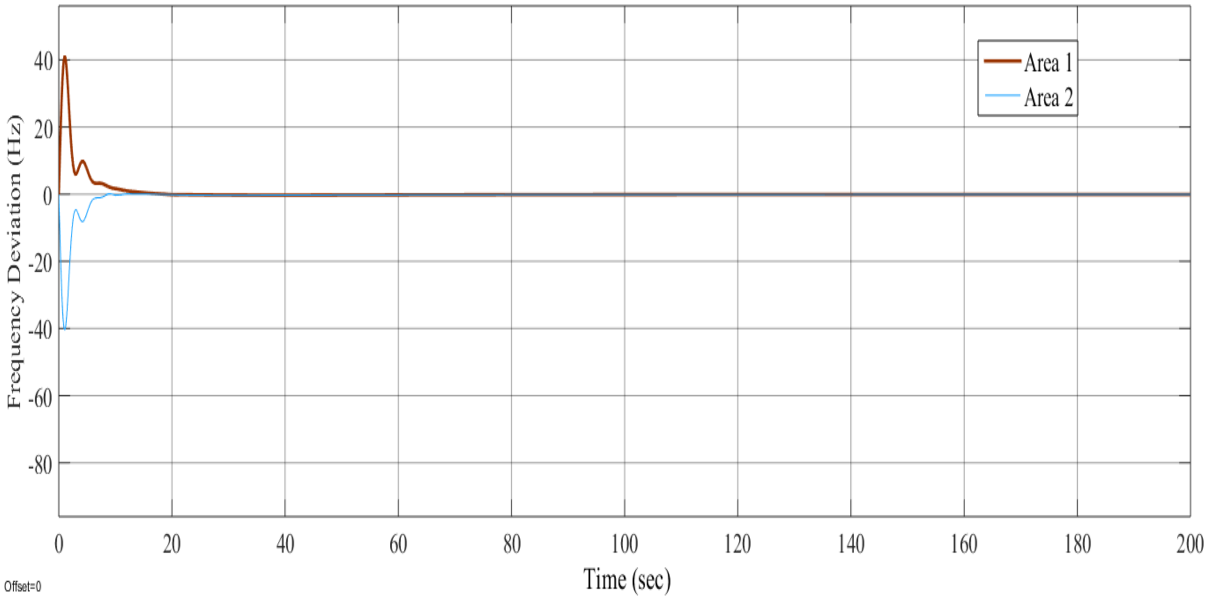

Figure 5.30 Frequency Deviation Characteristic with the application of PSO (TVAC) for 500 iterations

There is a large change in the settling time of the frequency characteristics with 500 iterations than 250 iterations. The frequency deviation characteristic with 500 iterations settles quickly below 20 sec. But the frequency characteristic with 250 iterations requires 30 sec to settle along with a kink at 20 sec. This characteristic takes more time than the previous one and the kink represents a small overshoot around 20 sec. Therefore, it can be said that the PI gains are better optimized with 500 iterations than 250 iterations though the computational time is more.

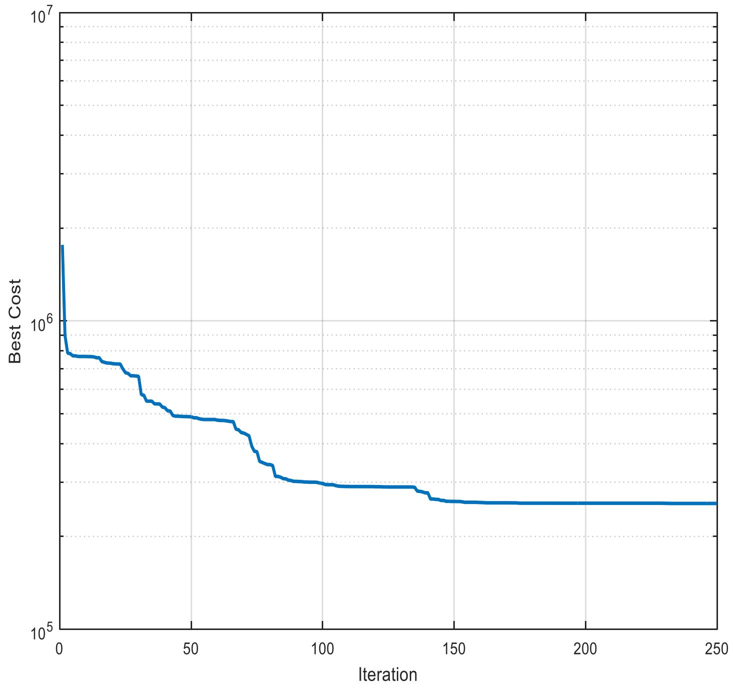

Figure 5.31 Convergence Characteristics for 250 iterations

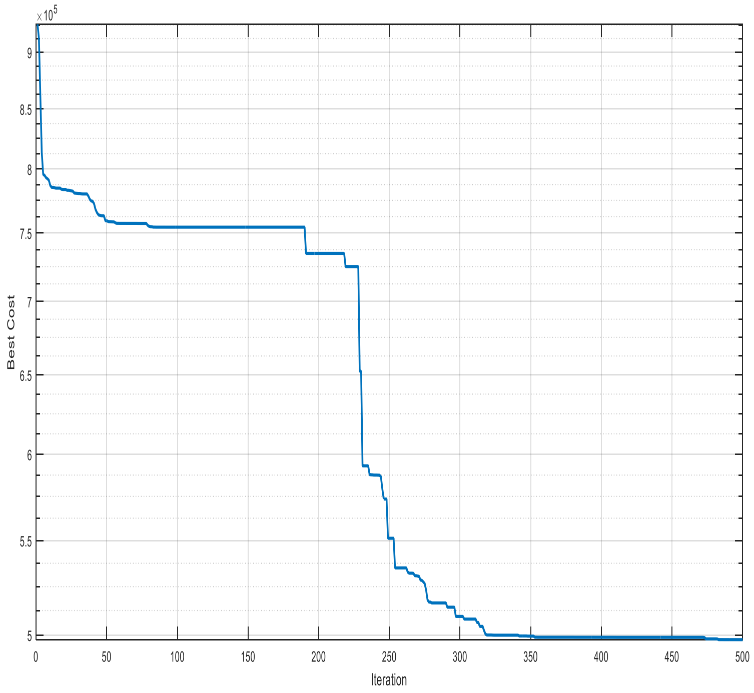

Figure 5.32 Convergence Characteristics for 500 iterations

Similar observations are found for the tieline power deviation characteristics as shown in Figure 5.33 for 250 iterations and in Figure 5.34 for 500 iterations. The system achieves the steady state earlier with modified PSO application and 500 iterations. With increase of iteration numbers the tieline power interchange between the areas are around 10 MW whereas for 250 iterations it is 8 MW.

Figure 5.35 and Figure 5.36 depict the generation deviations. Here also the characteristics get improved with 500 iterations i.e. the deviations in the generated output power are reduced.

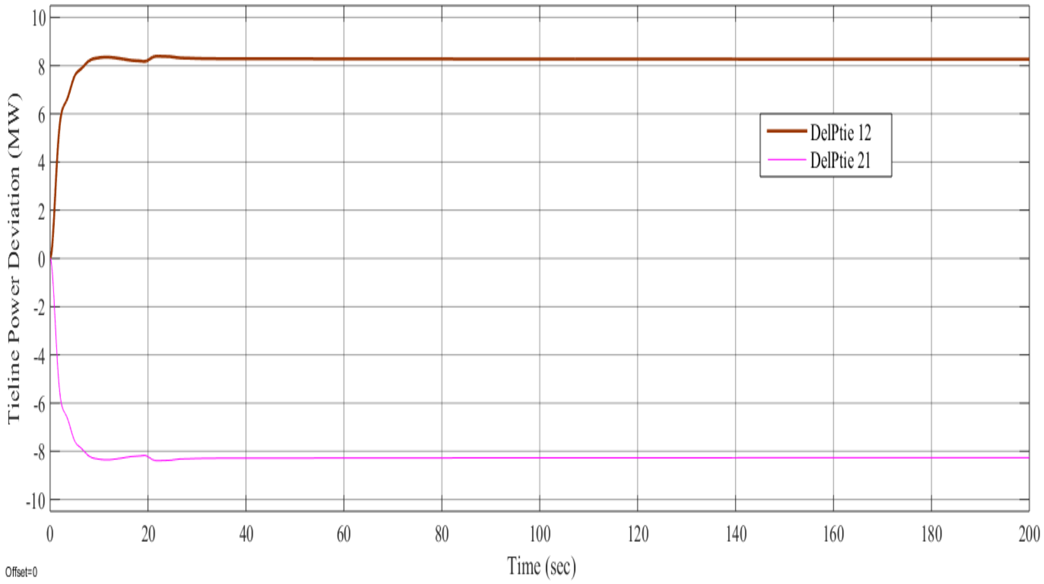

Figure 5.33 Characteristics of the Tieline Power Deviation with the application of PSO (TVAC) for 250 iterations

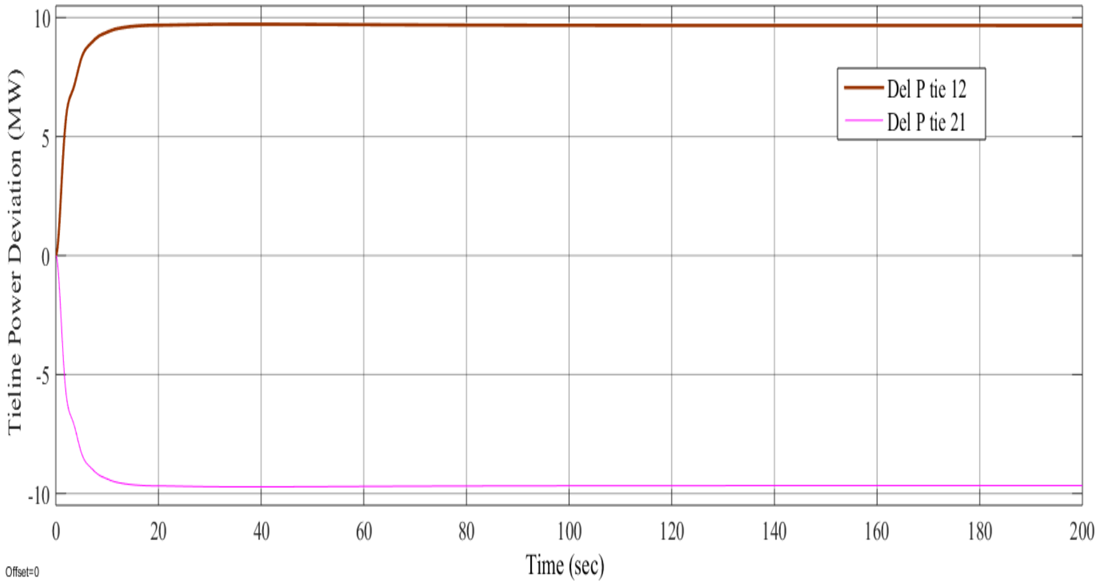

Figure 5.34 Characteristics of the Tieline Power Deviation with the application of PSO (TVAC) for 500 iterations

From Figure 5.35 it is clear that there is no deviation in hydro generation output and the change in the thermal generator 1 and the thermal generator 2 output are equal and opposite. The wind power output remains constant with no change in the wind speed. Figure 5.36 shows that the deviation of thermal generator 1 and hydro generator outputs are equal and negative. The change in the thermal generator 2 power output positive. The change in tieline power flow between the area 1 and area 2 is equal to the wind power output.

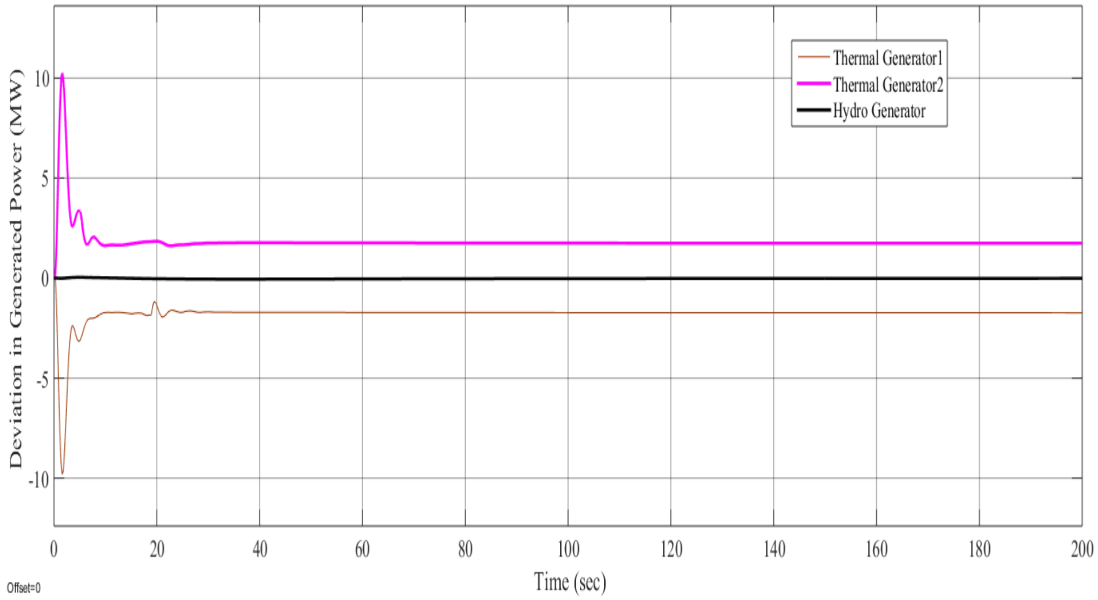

Figure 5.35 Changes in Generated Power (MW) Deviations with PSO (TVAC) for 250 iterations

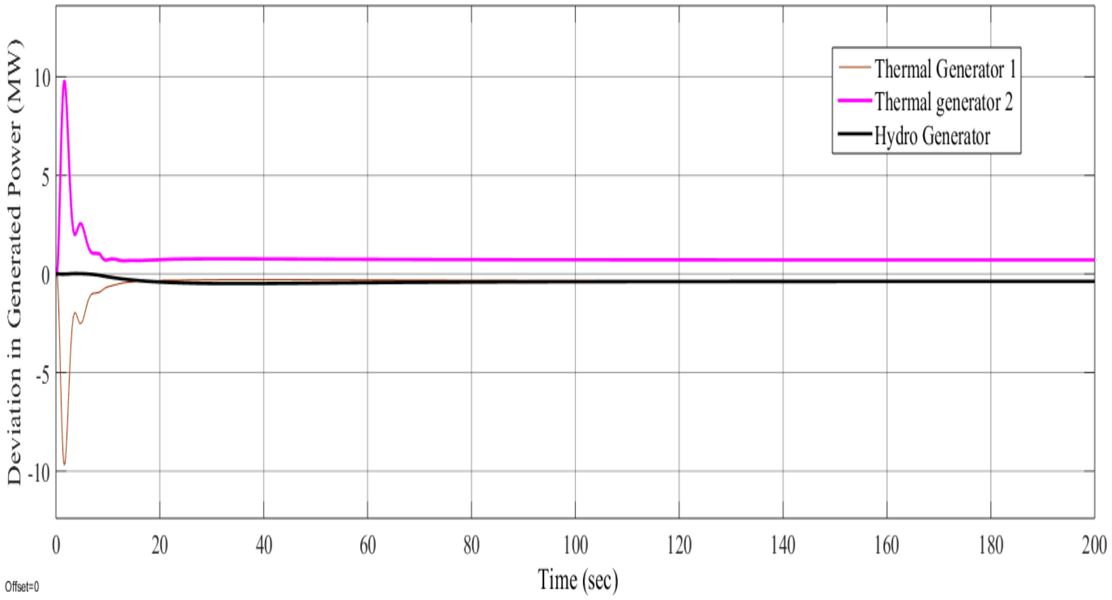

Figure 5.36 Changes in Generated Power (MW) Deviations with PSO (TVAC) for 500 iterations

The modified PSO program has minimized the generation control error (GCE) (Figure 5.38) and in turn optimised the PI controller gains. The GCE measures of the incentive to be received by the generators during the peak load hours by supplying more to the grid or calculates the penalty charge for generating less during the peak hours and not helping in the improvement of the grid frequency. Hence, minimizing the GCE for the sake of grid discipline is an important task of the controller. Without the PSO optimised controller gains the GCE characteristic appears as shown in Figure 3.37. Though the GCE characteristic shows initial overshoots, it settles within few seconds with PSO (TVAC) application and becomes zero quickly. With 500 iterations this characteristic achieves better convergence and settling time. Thus the proposed PSO optimized system is found to be an efficient system where the generators will neither profit unaccountably nor the power system will lose the grid indiscipline. Hence, the grid frequency stability and the power economy are maintained simultaneously under ABT regime.

The earlier four case studies have focused on the frequency stability and the tie-line power flow characteristics with or without renewable generators using the UI price based secondary-frequency-control. It has also encompassed the influence of the PSO optimization on the system dynamics and the generation control error (GCE) (Figure 5.38). Next, the effect of the wind penetration on the Unscheduled Interchange (UI) rate has been simulated in an Indian context to make the proposed interconnected-power-system and its study for increased wind power penetration more realistic.

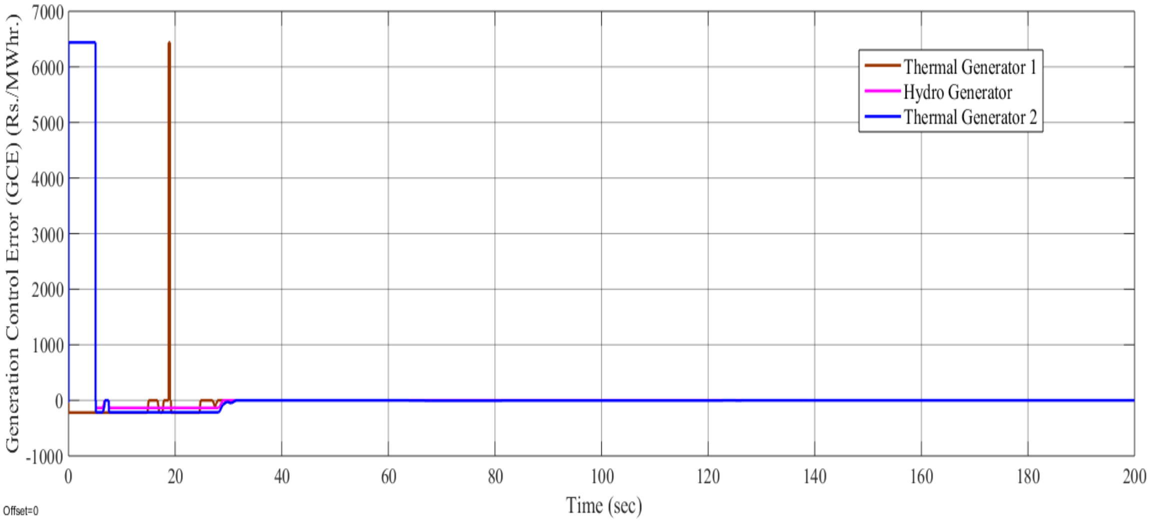

Figure 5.37 Generation control Error (GCE) without the application of PSO

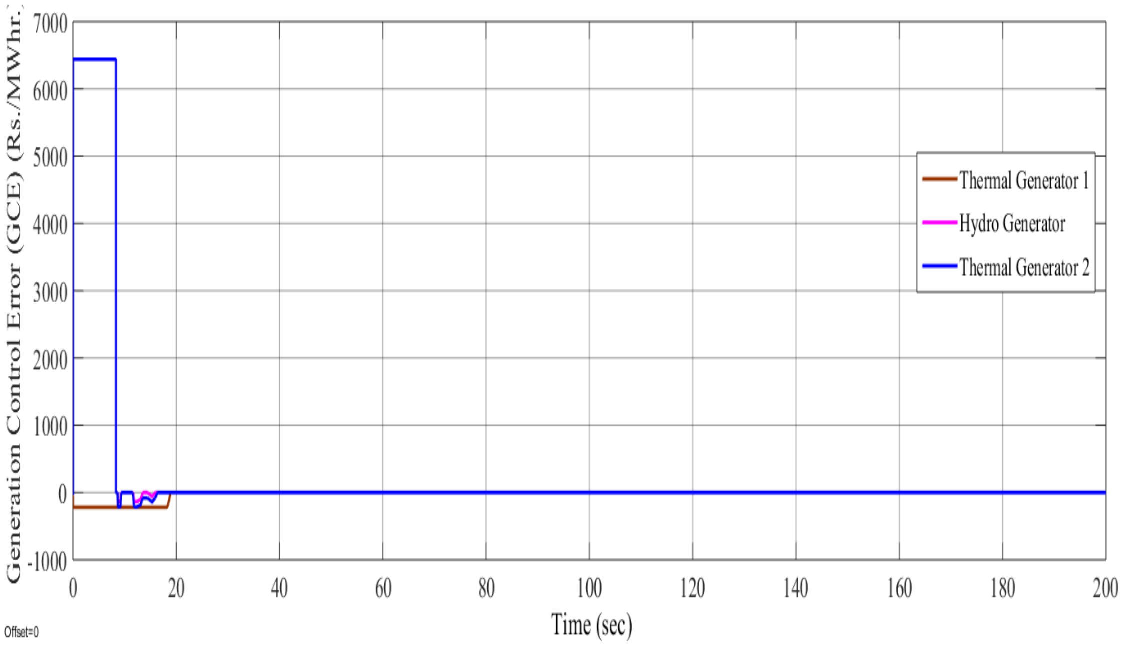

Figure 5.38 Generation control Error (GCE) using PSO optimized PI controller Gains

5.5 Case5: Wind Power Penetration Effects on the Unscheduled Interchange Rate in an Indian Two Area Interconnected-power-system

This section uses a three area thermal-hydro-wind based interconnected-power-system already described in chapter 3. The constants used in the transfer functions of the complete block diagram are shown in Table 5.6. The generator capacities are chosen as per Table 5.7. As described in the earlier sections, the wind turbine generator operates only on the primary control loop as its input is intermittent in nature. Therefore the WTG is kept outside the ABT loop as its availability is not confirmed. Other five generators participate in the ABT based secondary-frequency-control loop. The wind power with 15% penetration in the area1 is studied. The change of 10 MW in demand in area 1 and area 2 are considered whereas a change of 4MW demand in area 3 has been set. The same system is studied through simulation for the changes in wind power input also. The consequent rate of unscheduled interchange charges has been evaluated. All these are done through the dynamic simulation of the interconnected-power-system using UI price based secondary control. The proposed interconnected-power-system is investigated to study the wind power penetration effect on the other generators' output and on the UI charges when the system is subjected to the load changes. Table 5.8 describes all the gains and the different time constants used to develop the transfer function models of the thermal generators, the hydro generator, diesel/biomass generator and the wind generator parameters. Table 5.9 shows the capacities of the generators.

Table 5.8 Gains and the Time Constants of all the Generators used in the Thermal-Hydro-Diesel/Biomass-Wind based Interconnected-Power-System

Generator	Parameters	Values
Thermal	The Governor Speed Regulation	3
	Speed Governor Gain	1
	Speed Governor Time Constant	0.3 s
	Dead Band Parameters of the Generator N1, N2	0.8, -0.2
Hydro	Time Constant of the Hydro Speed Governor	48.7s
	Time Constant of the Hydraulic Amplifier	10 s
	Dash Pot Decay Time Constant	0.5 s
	Water Starting Time	1 s
Diesel/Biomass	Generator gain and Time Constant	1 and 0.24 s
	Reheater Gain and Time Constant	0.33 and 10 s
	Governor Gain and Time Constant	1and 0..08s
Wind	Time constant of the Washout filter	6 s
	Time Constant of the Frequency Transducer	0.1 s
	Controlled WECS Gain and Time	3.5 and 0.2 s
	Proportional Constant of the Speed Regulator	1.5
	Integral Constant of the Speed Regulator	0.15 s
PowerSystem	Gain	120
	Time Constant	20s

Table 5.9 Generator Capacities for Case5

Thermal Generator	Hydro Generator	Diesel Generator	Wind Generator
200 MW (in Area 1 and 3) and 100 MW in Area 2	150 MW	60MW	60MW

5.5.1 Frequency and Tieline Power Deviation due to Sudden Load Change

The frequency deviation and tie-line power flow deviations due to sudden perturbations in load in all areas are simulated and shown in Figure 5.39 and Figure 5.40 respectively. The corresponding frequency deviation and the tieline power deviations are also presented in Table 5.11 and in Table 5.12 respectively. The frequency deviation characteristic stabilizes at 80 s. Figure 5.40 shows the tie-line power deviation between three areas. These characteristics resemble similar nature that some of the earlier case studies. The tie-line power flows from area 1 to area 2 majorly and very small tie-line power flows from area 3 to area 1. The tie-line power flowing from area 3 to area 2 is comparatively higher. But the final tie-line power deviation at the steady state is nil. The dynamic power flow deviation characteristic settles rapidly due to the inertia of the power system entities. The presence of the unscheduled interchange (UI) based secondary-frequency-control can cause of the larger response times of the frequency characteristics and tieline power deviation characteristics. The inclusion of DFIG wind turbine generator reduces the grid inertia. The variable speed WTG with static converters for variable speed operation deals with the improved ancillary services. But, the inclusion of converters decouples the turbine rotor from the power system. Thus the system inertia is reduced. Hence emulating inertia is used for connecting DFIG with the interconnected-power-system. The effect of the increased wind power penetration has been studied in 5.5.2.

5.5.2 Effect of Wind Penetration Levels on Unscheduled Interchange Rate

The unscheduled interchange price rate in Rs./MWhr has been tabulated in Table 5.10 at different wind penetration (%). The wind penetration in area1 rises for the load changes as described in the section 5.5.1. With the increase of wind penetration, the response times of the frequency deviation characteristics become more. As the inertia offered by the DFIG based WTG system is less the system responses take more time to settle. The system responses get slow because of the cause mentioned here.

In the frequency-linked-pricing criteria, the generator yields its own rate of unscheduled interchange price in Rs./MWhr. This rate follows the UI price curve published by government. As this work is done in the Indian context, the UI price curve imposed by Government of India has been used. During the steady state condition as the frequency characteristic reaches the nominal value of grid frequency, the UI price also remains fixed.

The Marginal Costs of the generators are also simulated for different load perturbations. The marginal costs of the convention generators are determined and linked with the MATLAB/Simulink block diagram. Table 5.10 shows the unscheduled interchange costs.

Table 5.10 Unscheduled Interchange at Different Wind Situation

Wind Penetration (%)	Load Perturbation	Rate of Unscheduled Interchange Price (Rs./MWHr.)					Settling Time (sec)
		G1	G2	G3	G4	G5	
0	Area1-10MW Area2-10MW Area3-4MW	220	220	220	220	220	50
8.33		220	220	220	220	220	80
25		220	220	220	220	220	90
50		219	219	219	217	217	100
75		219	219	219	220	220	110
100		219	219	219	217	217	110

G1: Thermal Generators in area1;

G2: Thermal Generator in Area2;

G3: Hydro Generator in Area2;

G4: Thermal Generator in Area 3;

G5: Diesel/Biomass generator in area3.

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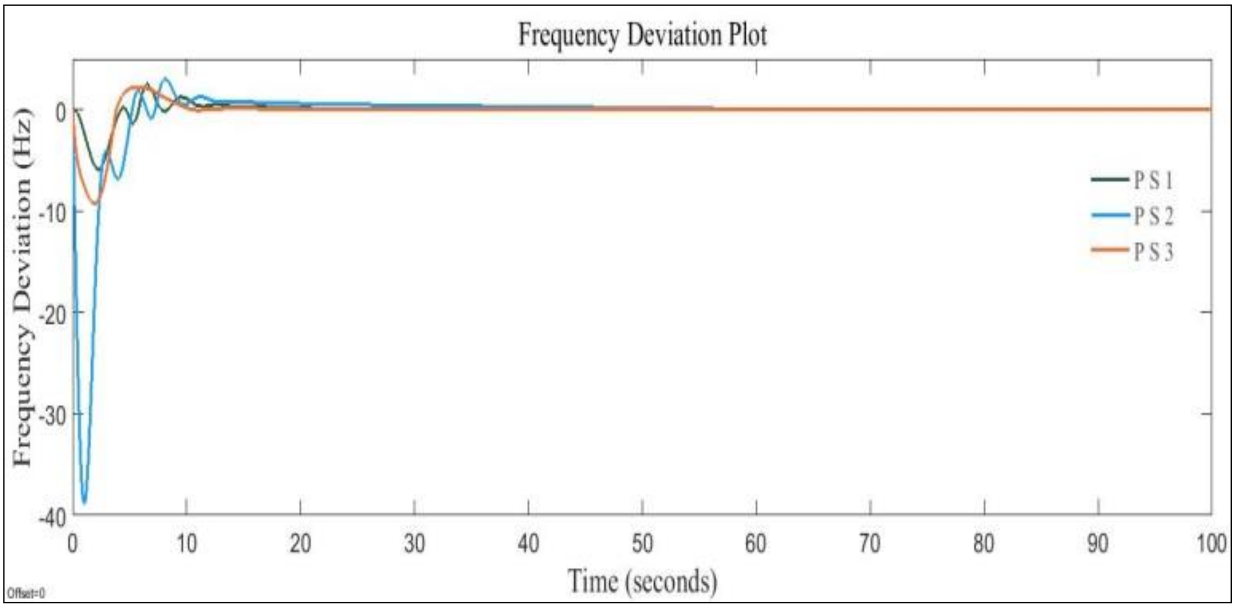

Figure 5.39 Frequency Deviation Characteristic due sudden perturbationof load

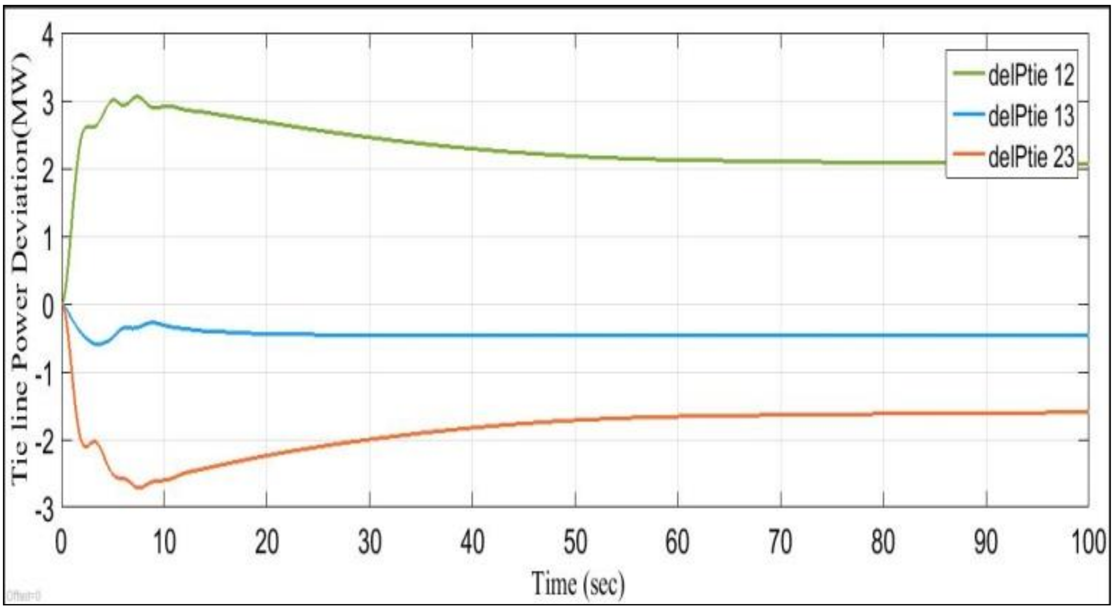

Figure 5.40 Tie-line power deviation characteristic

Table 5.11 Frequency Deviation Due to sudden Perturbation of load

Time (sec)	Frequency Deviation in Power System Area1(PS1) (Hz)	Frequency Deviation in Power System Area2(PS2) (Hz)	Frequency Deviation in Power System Area3(PS3) (Hz)
0	0	0	0
0.9605	-2.12	-38.79	-0.7404
1.868	-5.424	-20.31	-9.266
2.21	-5.902	-11.31	-9.021
2.987	-4.282	-3.976	-5.975
3.185	-3.486	-4.45	-4.713
3.837	-1.173	-6.824	0.001128
3.948	-0.6875	-6.825	0.3873
4.177	-0.1085	-6.502	1.037
4.257	0.619	-6.243	1.212
5.15	-1.311	0.2257	2.153
5.206	-1.327	-0.1185	2.158
5.285	-1.362	0.4027	2.179
5.751	-1.337	1.932	2.213
6.44	2.459	0.1442	2.108
6.521	2.5	-0.121	2.086
6.936	1.96	-0.8695	1.927
7.2898	0.9845	0.2858	1.717
8.104	-0.1583	3.021	1.171
9.807	1.211	0.4712	0.2759
10.11	1.011	0.6087	0.1548
10.63	0.584	1.042	0.001808
11.49	0.3234	1.241	0.01847
15.5	0.2717	0.7552	0.1224
19.45	0.1371	0.612	0.03574
25.86	0.0418	0.4796	0.02376
29.98	0.03595	0.4244	0.02084
39.81	0.02212	0.2997	0.01435
49.66	0.009129	0.1758	0.007895
59.52	-0.002892	0.06269	0.00334
69.38	-0.007308	0.03183	-0.007198
79.24	-0.008532	0.01961	-0.008473
89.1	-0.009853	0.01161	-0.009345
98.96	-0.009895	0.00653	-0.009898

Table 5.12 Deviation in Tie line Power Flow between three Areas

Time (sec)	Tie-line Power Deviation between area 1 and 2 (DelPtie 12) (MW)	Tie-line Power Deviation between area 1 and 3 (DelPtie 13) (MW)	Tie-line Power Deviation between area 2 and 3 (DelPtie 23) (MW)
0	0	0	0
0.6701	0.6162	-0.1275	-0.4886
0.8807	0.984	-0.1838	-0.8001
1.218	1.59	-0.2716	-1.319
1.544	2.083	-0.3498	-1.733
2.385	2.613	-0.503	-2.11
3.385	2.632	-0.5945	-2.038
3.594	2.669	-0.5969	-2.072
5.095	3.012	-0.4826	-2.524
5.907	2.934	-0.3617	-2.573
7.419	3.061	-0.3567	-2.713
10.11	2.919	-0.3193	-2.6
19.45	2.692	-0.4398	-2.253
25.86	2.542	-0.4538	-2.088
29.98	2.457	-0.4569	-2.00
39.81	2.292	-0.4618	-1.83
49.66	2.183	-0.4638	-1.719
59.52	2.126	-0.464	-1.662
69.38	2.103	-0.4641	-1.639
80.88	2.84	-0.4641	-1.62
84.17	2.08	-0.4641	-1.616
89.10	2.074	-0.4641	-1.61
95.67	2.068	-0.4641	-1.604
98.02	2.068	-0.4641	-1.604

Table 5.13 shows that as the wind penetration increases, the burden on the other fossil fuel based generators supplying the base load decreases. Marginal cost is calculated based on the power generation of each generator .Thus the marginal costs of the generators decrease as the wind penetration is increased. Thus the frequency regulation can be achieved in more economical manner. Hence the UI based secondary-frequency-control can imply that the wind turbine generator can help by providing more power to the interconnected system and reduce the dependency of the power system on the other conventional generators. Though it is not participating in the ABT loop, still it can help to reduce the burden on the other generators in an economical way.

Table 5.13 Marginal Costs of the Generators at different Wind Penetration

Wind Penetration (%)	Load Change	Marginal Cost (Rs./MWhr)				
		G1	G2	G3	G4	G5
0	In Area1-10MW In Area2-10MW In Area3-4MW	220.5	215.4	137.6	220.32	156
8.33		220.4	215.3	137	220.3	154.65
25		220	215	136.4	220	152.2
50		219.75	214.9	135	219.9	148
75		219.5	214.1	134.3	219.5	144
100		219.3	214	133.4	219.2	140.4

.

Microgrids have entered the power system scenario with distributed generation and new communication technologies. Though its generation capacity is lower compared to the main power grid components, it plays important role in sustainable power generating system to mitigate the power imbalance incorporating the renewable energy resources along with the storage systems. Hence the next part of this thesis deals with the incorporation of the microgrid in the interconnected-power-system as one of the generators in one power system area.

5.6 Case6: Frequency Regulation of Interconnected-power-system incorporated with Renewable based Micro-grid Under Availability-based-tariff

The system configuration of the proposed system has been already described in Chapter 3. The capacities of all the generating units are presented in Table 5.14. Table 5.15 presents the constants of all the transfer functions used in this study. The gains of the storage system transfer functions are considered negative here. The negative gain indicates that with the increase in input, the output would decrease. The same happens with the storage system change in power output versus change in frequency characteristic.

Table 5.14 Capacity of Generators Interconnected in the Microgrid incorporated Three Area Power System

Sl. No.	*Type of the generator*	*Capacity*	*Quantity*
1	Thermal generator	150 MW	3
2	Hydro generator	100 MW	1
3	Off-shore Wind generator	6 MW	10
4	Fuel cell	2.8MW	5
5	Diesel generator	3.6MW	2

The thermal plants support the base load of all areas. Wind generator input is unpredictable. Hence it has been modelled with step inputs as well as with random variations. In this investigation, hydro plant normally operates with steady input though it may be shut down due to certain anomalous weather situation. Figure 3.7 depicts the three area interconnected-power-system. The off-shore WTG output is connected to the local grid through HVDC blocks as HCDC transmission is preferred over the HVAC transmission of power from the offshore wind generators to the local grid supply.

The active power demands are continuously changing in a power system which is met through regulating the steam or water input to in thermal or hydro power plants. Otherwise the generator speed would change following deviation in the frequency output. To bring frequency within normal grid frequency range, ABT based secondary-frequency-control is adopted in interconnected system instead of AGC. ABT based frequency control has been proposed in three area interconnected system incorporated with microgrid in this work. Three different cases related to three different situations frequently occurring in the interconnected-power-system have been studied here. The first case is studied to observe frequency and tie-line power flow deviations for load changes in all the three areas. Other two cases focus on the situation which would prevail in the interconnected system if the hydro generator and the wind generator stop producing power due to some natural hindrance. These cases have been studied following different load condition and availability of generator input.

5.6.1 Case6.1: Sudden change in load in all three power system areas

It is aimed to study the effect of changes in load in the proposed power system frequency and tie-line power when active power demands change in all areas. In all the areas sudden load changes are considered to follow step signals. Under normal operating condition, the load is taken to be 1.0 pu. Between 70s and 150s the load is decreased to 0.6 pu and again resumes 1.0 pu beyond that time [129]. During this period the wind speed also changes from 8 m/s to 10 m/s. The corresponding frequency deviation characteristic and tie-line power changes are studied here. Table 5.15 describes the gains and the time constants of the thermal generators, hydro generators and the components of the microgrid. Here the energy storage elements i.e. BESS and FESS transfer functions have negative gains. In the interconnected system the energy storage systems are getting charged during lean load period and discharge when demand is more. Therefore to model their transfer functions, gains must be kept negative so that for a positive step load change the direction of the output is negative. This would facilitate the charging and discharging sequence in line with the load changes.

Table 5.15 Control parameters of the Thermal, Hydro and Microgrid system

Sl No.	*Generator/energy storage device*	*Gain*	*Time constant (s)*
1	Thermal	1	0.3
2	Hydro	1	0.5
3	Wind	1	1.5
4	Fuel cell	0.01	4
5	Aqua electrolyser	0.002	0.5
6	DEG	0.003	2
7	BESS	-0.003	0.1
8	FESS	-0.01	0.1

The frequency characteristic of the interconnected area is shown in Figure 5.41. When the load is suddenly switched to 1pu certain underdamped response is observed, but it settles quickly. The properly chosen proportional and integral controller reduces the steady state error of this dynamic response and improves the settling time for a step load perturbation. Again at the second instant when the load change is decreased to 0.6pu another damped oscillation is observed. In response to every load change in the form of step input, the dynamic frequency response of the third order characteristics equation represented in the transfer functions of each steam and hydro generator result in the damped oscillation as shown in Figure 5.41. As the load is decreased frequency is increased initially, then settles to the steady state value due to the presence of the PI based feedback control operation. Before the frequency characteristic settles at a suitable time, wind speed changes around 100s followed by an increase in the demand round 150s. Therefore the frequency deviation characteristic does not settle exactly at zero. For these instants, if we would have chosen dynamic values of proportional and integral gains, then the steady state error would have reduced to zero quickly. In that case the PI gains would have been change with the changed frequency dynamic.

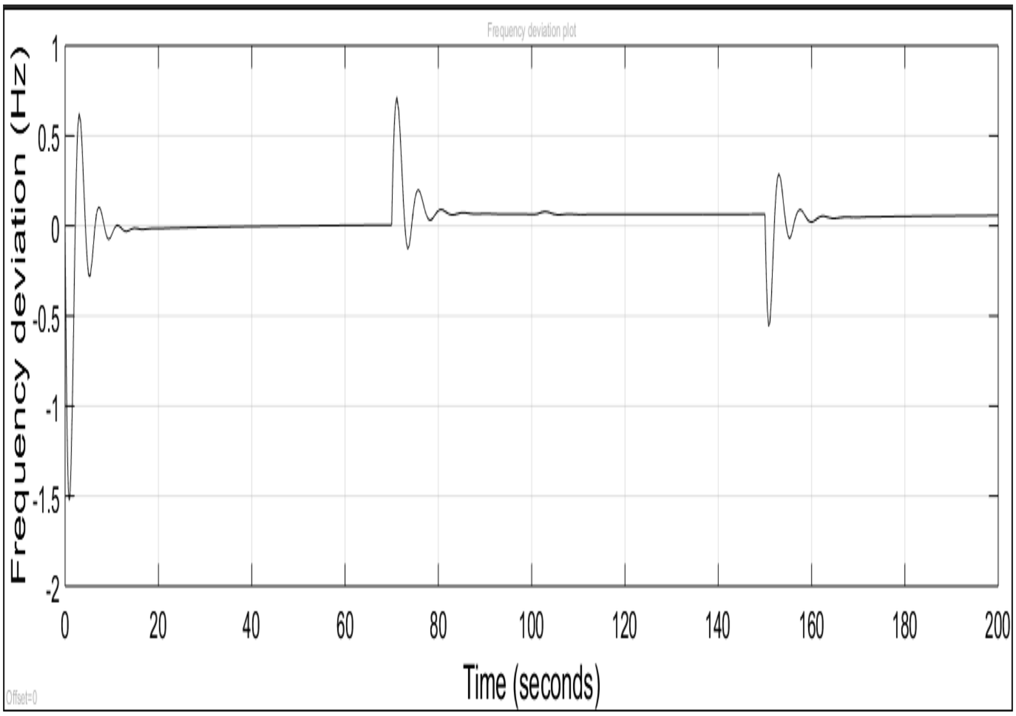

Figure 5.41 Frequency deviation due to perturbations of demand in the power system

When the load is switched on at the initial instant, all the generators and the microgrid have started increasing the power generation and reached the steady state value as shown in Figure5.43. Figure 5.42 depicts the consequent deviations in the tie-line power flow between the three areas. Tie-line power flows from area1 to area2 and area3. The tie-line power which flows from area2 to area3 gradually changes from negative to positive. As the hydro generator increases its change in generation gradually, the tie-line power flow from area2 to other two areas increases. When load is decreased at 70 second, the steam generators decrease their generation owing to load frequency control phenomenon and the change in tie-line power flow from area 2 to area 3 and area 1 increase. It may be due to the fact that the rate of change in power generation in hydro generator is more than the others as area2 has the hydro power generator.

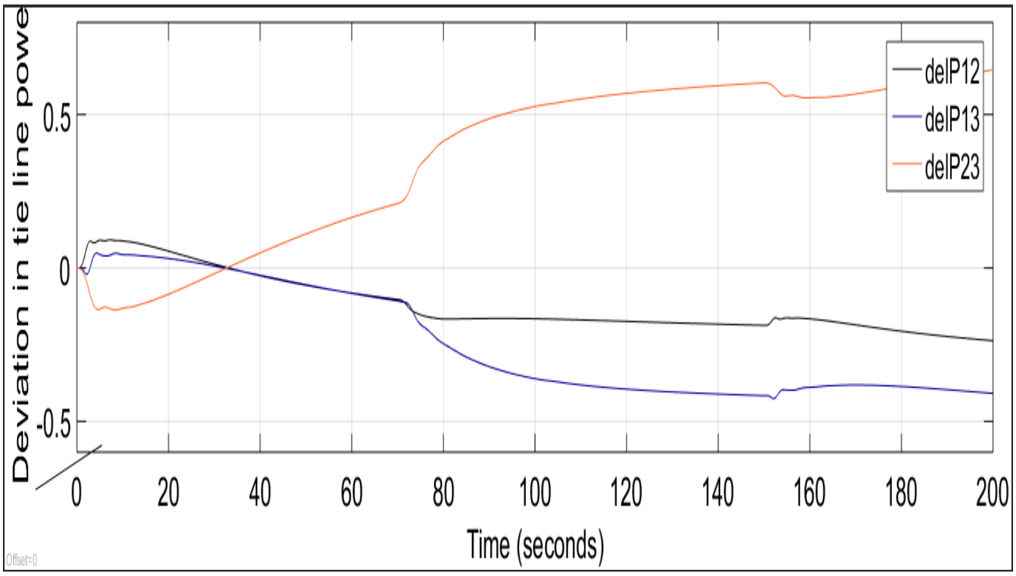

Figure5.42 Tie-line power characteristics due to sudden change of load in all areas

In Figure 5.43 it is observed that the microgrid power has become negative after the load in all the three areas have decreased at 70 sec suddenly. The decreased load in the third area is supplied by the thermal generator connected in area 3 (Th4) and the tie-line power. The two energy storage devices connected in the proposed microgrid of this area, are now charged by the power from tie-line and its own generator. That is why the microgrid power is negative here.

During some season, the water flow in the rivers may reduce due to lack of rainfall or sometimes it increases due to heavy rainfall. Hence the water input to the hydro turbines fluctuate and its output changes. In the next case such a situation has been considered when the hydro turbine is being disconnected due to shortage of rainfall.

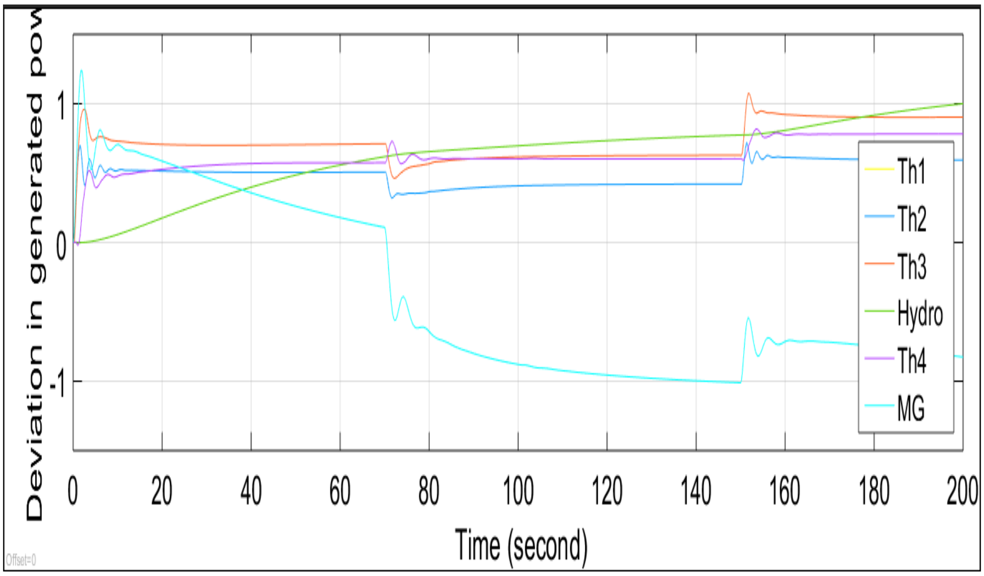

Figure 5.43 Deviation in power generated in all the generators connected in this system along with the microgrid

5.6.2 Case6.2: Hydro Generator disconnected

The study of disconnection of hydro generator from area 2 is done to observe the effect of intermittent nature of hydro power input at different weather condition. This phenomenon is very common in Indian scenario. Figure 5.44 depicts the frequency deviation characteristic for the interconnected system when the hydro generator of area 2 is disconnected. The characteristic settles quickly after the changes in demand. The secondary-frequency-control loop of the thermal and hydro generators work based on the UI rate which makes the system response slower compared to the normal load frequency control (LFC) system. When hydro generator is disconnected, the power input in the area 2 is decreased. Hence the entire change in the power generated in area 2 is accommodated through the thermal generator connected in this area and the rest is supplied through the tie-line power flow from other areas. This change in input achieves quick settlement as the unscheduled interchange based secondary control holds good unless there would more overshoots/undershoots and more settling times in the frequency characteristics as discussed next.

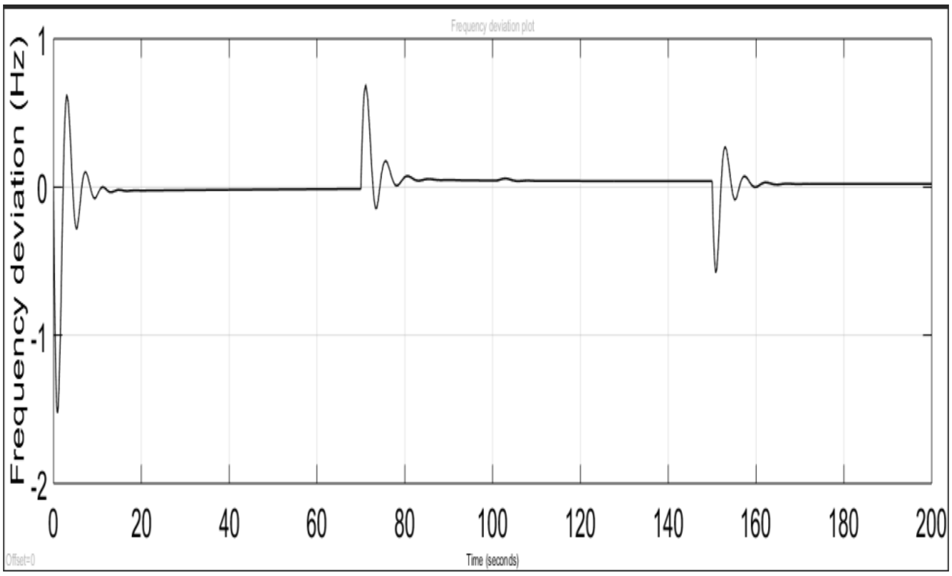

Figure 5.44 Frequency deviation characteristic with no generation from the hydro power generator

Figure 5.45 shows the deviation of power generated from different generators when hydro is not generating power due to certain natural calamities. The change in load in all the three areas is same that of case1. Comparing Figure 5.43 with Figure 5.45, it can be said that the share of the generators other than the hydro generator have been increased or decreased to accommodate the increment or decrement in the load. Here microgrid power is positive initially when the load is increased but becomes negative when the load is decreased. The explanation is same as before, i.e. when the load is decreased the other generators meet the decreased demand and the energy storage devices connected in the microgrid are charged.

The tie-line power flow between three areas is shown in Figure 5.46. It shows that when load change is increased suddenly at first, power flows from area 1 and area3 to area2. As the hydro generator is disconnected, the increase in increase in load is compensated by the power generated in other two areas according to their capacities. When load decreases at 70s, the power flow between area1 and area3 and between area1 and area3 get reversed. The load change in area1 is more than that of area3. Therefore, area3 supplies area1 after satisfying its own load change. The major change in power flow is observed between area2 and area3 whose capacities are comparable. Area3 also supplies area2 in this situation when hydro generator of area2 is disconnected.

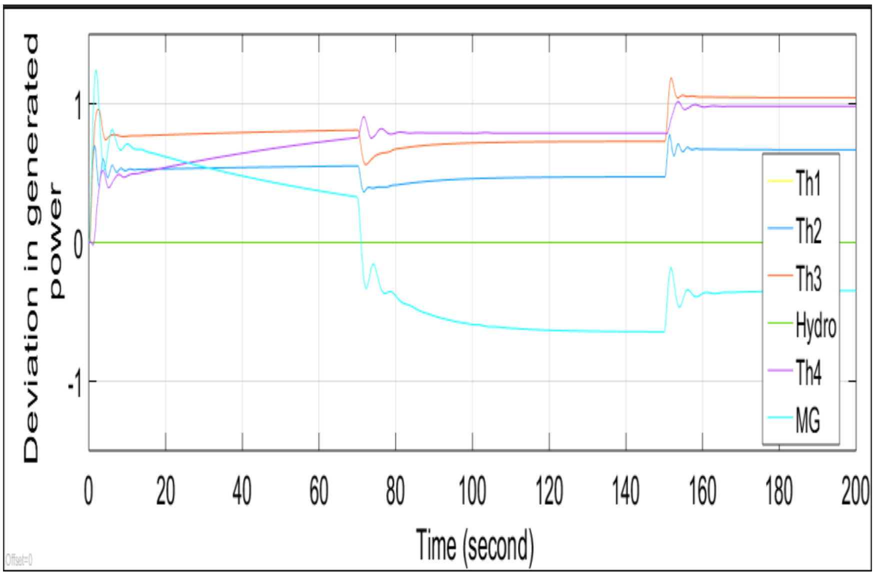

Figure5.45 Deviation in generated power when the hydro generator is disconnected

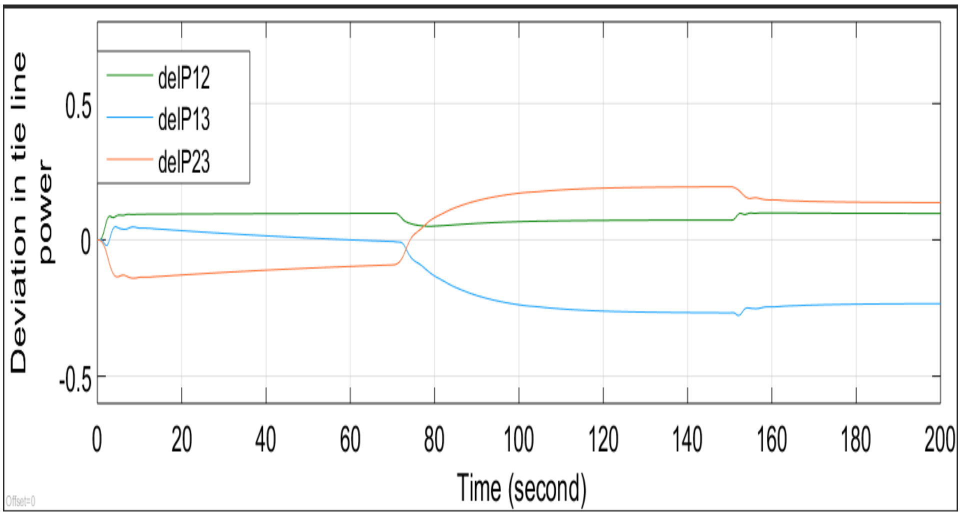

Figure 5.46 Deviation in tie-line power with no generation from the hydro generator

5.6.3 Case6.3: Wind generator of the Microgrid disconnected

Wind speed varies from season to season. In some times of the year the wind speed may go below the cut off speed. In that situation the wind generator output does not contribute to the grid power. So the disconnection of the wind turbine generator from the microgrid has been considered here.

In this case the off-shore wind turbine generators (WTG) considered are connected to the microgrid through HVDC link. Due to certain faults at the HVDC link, the wind farms are disconnected from the microgrid. This case deals with the situation when the capacity of the microgrid connected in area3 has been reduced by 60 MW. In such a situation the effects of load changes are observed as shown in Figure 5.47, Figure 5.48 and Figure 5.49.

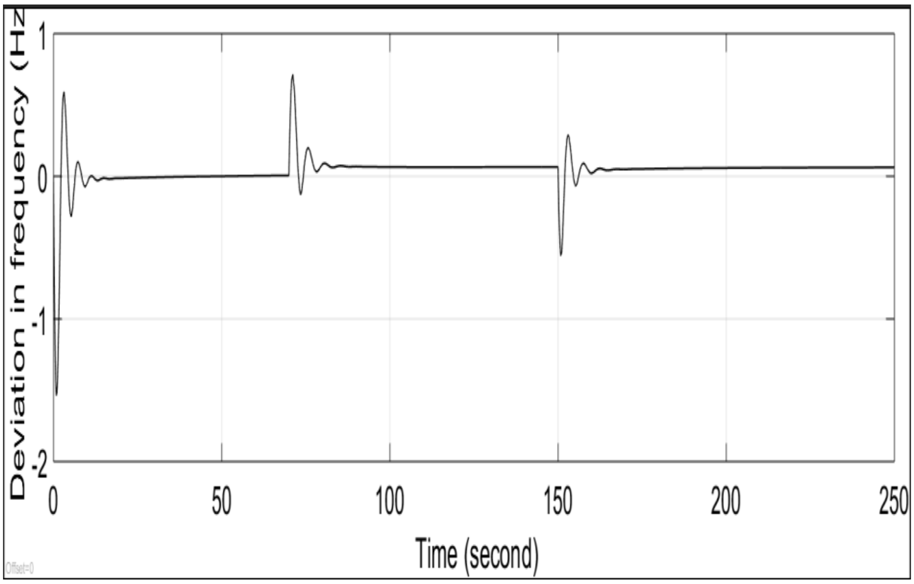

Figure5.47 Frequency deviation characteristic when the WTG is disconnected

Figure 5.47 presents the frequency deviation characteristic when the wind generator is disconnected for the same load change in all the three areas that of case6.2. The generation capacities of area1, area2 and area3 are 300 MW, 250 MW and 171.2 MW respectively in this case i.e. area3 has least generation capacity as the wind is disconnected from here. Therefore, the majority of load change is accommodated by area1 and area2 and the disconnection of wind generator does not have much effect on the interconnected-power-system. As the load variation pattern remains the same that of the earlier cases, the frequency deviation characteristic also shows similar damped oscillations at the instants where the load has changed suddenly. The overshoots and the undershoots are observed in the Figure 5.47 at the places where there are sudden changes in load which has been modelled as the step load changes.

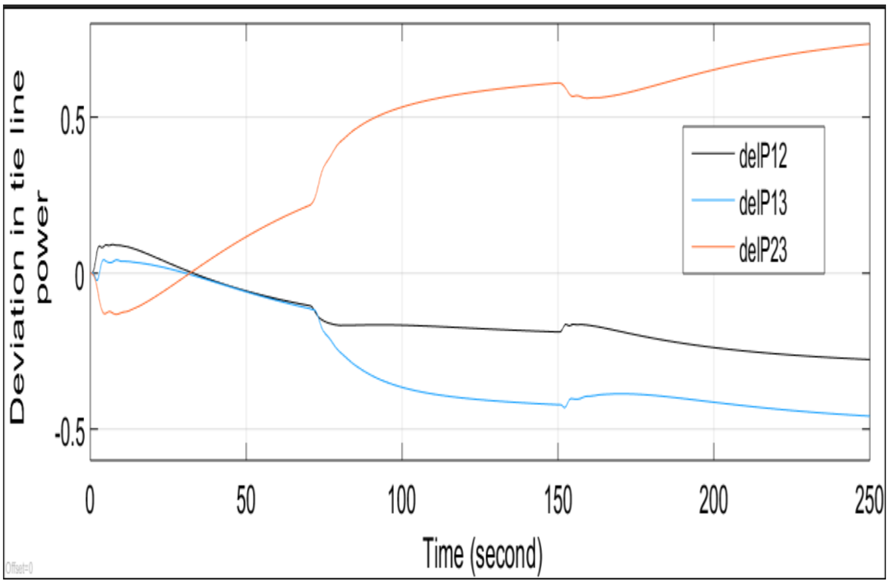

Figure 5.48 Characteristics of the tie-line power with no generation from the wind power generator

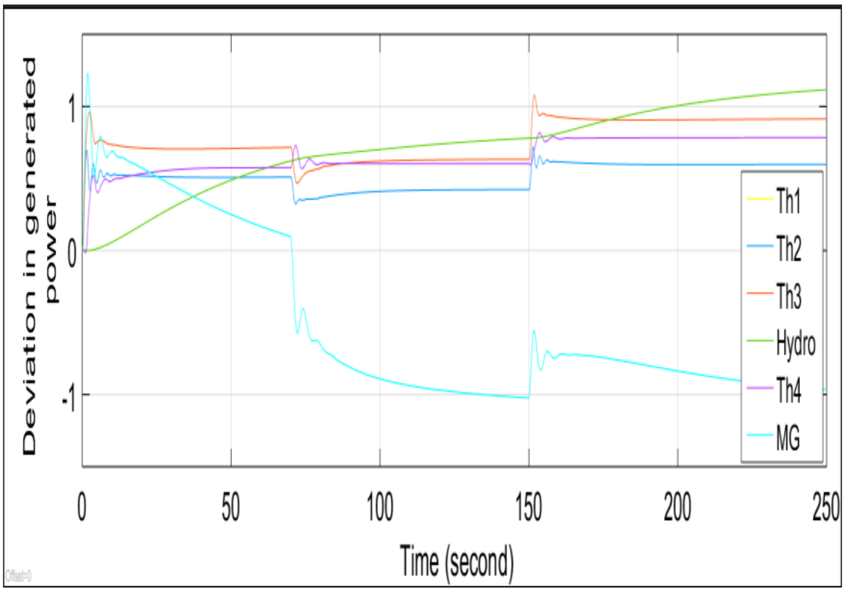

Figure 5.49 Deviation in power generated in all the generators connected in this system along with the microgrid when wind generators are disconnected

Figure 5.48 shows the deviations in tie-line power flow during no generation from the wind farms. Since the renewable energy resources are stochastic in nature, no availability based control regulations are imposed on them. The contribution from microgrid in area 3 as well as in the interconnected system is reduced due to disconnection of wind farms. But this reduction is adjusted through other generators of the microgrid and the other areas. Neither wind generators nor the other generators of the microgrid are subjected to the unscheduled interchange based secondary-frequency-control mechanism. The UI based frequency control is applied only to thermal and hydro generators. Hence wind generator disconnection does not affect much in the pattern of the output of generators (Figure 5.49), only magnitudes are changed slightly. Owing to the same reason deviation in tie-line power flow (Figure 5.48) also follows the same pattern that of the case studied in 5.6.1. Thus different load conditions and the wind/hydro generator connection/disconnections are simulated in the MATLAB/Simulink platform for this renewable energy based microgrid incorporated interconnected-power-system.

All the six cases studied in this thesis are focusing on the frequency regulation of the interconnected-power-system, its constituent areas comprising conventional as well as renewable energy resources including microgrids, dynamics of tie-line power flow and finally the effects of availability-based-tariff (ABT) on the interconnected-power-system as described. The results infer that ABT can be applied on the proposed systems described in different sections suitably for maintaining the grid discipline in terms of the frequency regulation, power generation and tie-line power flow. Thus the simulation results of all the case studies are depicted in this chapter. The next chapter gives overall conclusion on the work presented in this thesis.

Chapter 6:Conclusions And The Future Scope Of Work

6.1 Conclusions

In this research work, six different case studies have been investigated for interconnected multiarea power system with or without renewable energy resources. When several government owned and private power producers are delivering power to the grid, then the grid stability in terms of frequency fluctuations, tie-line power deviations and the generation deviations should be maintained using proper control schemes. The conventional automatic generation control (AGC) method area control errors (ACE) are considered and the controller parameters are optimized through heuristic and meta-heuristics techniques. In this work, instead of ACE, generation control error (GCE) has been used. This signal is generated combing the effects of the frequency deviation and the deviation of the actual generation from the scheduled one. The GCE has been minimised using PI controllers. PI controller parameters are optimised either using the Ziegler-Nichols (ZN) technique or PSO.

Case1 to case6 are tested under availability-based-tariff (ABT) regime using MATLAB/Simulink. Here the interconnected systems are subjected to the generation-demand imbalance. The sudden change in the load in all areas under different power generation scenarios forces the grid frequency to fluctuate and as a consequence the power generations and the tie-line power flow between the areas are perturbed. Under these disturbances the unscheduled interchange based pricing criterion has worked satisfactorily to improve the grid stability. Though the UI price based control has made the system responses slower compared to the conventional AGC, still it has established the grid discipline and the modified the generation.

These revised generations from the thermal, hydro, diesel/biomass generators have enabled them to get incentives for mitigating the frequency fluctuations. Hence the controlled generations by these conventional generators restrict the use of the fossil fuel. As the fuel uses are limited the cost of generation is also reduced and this can help to make the electricity affordable for a greater population worldwide. Such situation is helping to achieve the seventh Sustainable Development Goal (SDG 7).

Case1 has shown the effect of UI price on the frequency control and case2 has focused on the tie line power flow for greater numbers of interconnected power system areas. This research work has incorporated wind power generation in the interconnected system in case3, case4, case5 and case6. Though the WTG does not contribute to the grid inertia directly like the conventional synchronous generators used here, its primary-frequency-control method has used the emulating inertia and contributes to the grid inertia indirectly. As the availability of the wind is intermittent in nature, it is not incorporated in the UI price based secondary control. The integration of wind power in the interconnected-power-system has maintained the frequency dynamics when the load has changed suddenly. It has made the system response slower compared to the cases without wind power. So the ABT based frequency control can be applied for the wind integrated power system.

The studies done in case 5 reveal that the increased wind penetration has reduced the marginal cost of generation of the conventional generators though the settling time has increased. Thus the ABT based frequency regulation can work for the wind integrated power system operation. The RE integration scheme proposed here can lead to restrict the climate change and hence this work can contribute to achieve SDG 13.

All these case studies have led to a situation where the optimization of the PI controller parameters has become necessary to get better settling time of the system dynamic responses. The particles swarm optimization (PSO) technique has been applied in one case and it has showed huge improvement in the settling time of the system responses. Thus a successful application of ABT criterion in the frequency regulation of an interconnected-power-system with renewable energy integration has been achieved in this thesis.

Moreover the microgrid application having offshore wind power plants, fuel cell, aqua electrolyzer, diesel/biomass generator and two types of energy storage systems (FESS and BESS) has been done satisfactorily in the last case study. Hence the RE based microgrid also has an opportunity to operate within the interconnected-power-system operation in the ABT regime.

Finally it can be concluded that the availability-based-tariff can be suitably used for the frequency regulation and the economic power generation for multiarea interconnected-power-system operation with RE integration successfully.

6.2 Future Scope of Work

The research work carried out in this thesis can be extended in future to integrate more numbers of renewable energy resources other than wind, fuel cell, biomass generators etc. Due to the stochastic nature of the wind speed the availability of the wind power for the next day cannot be declared beforehand. But studying the wind pattern of an area and preparing a prediction model of the wind availability, the wind generator can be incorporated in the ABT based secondary-frequency-control scheme. This will improve the grid discipline a lot when the interconnected-power-system is subjected to the generation-demand imbalance.

Another future scope of the work is to use other optimization techniques to optimize the controller parameters and compare the results. This will make the system to become more rapid, efficient and reliable. The improvement of the system parameters can ensure better system response when the load change occurs or any power system area is disconnected due to a fault or there are changes in the RE based generations. In that case the controllers can be chosen based on their performances.

In this thesis the base load is catered by the conventional generator, mostly it is the thermal generator. With the paradigm shift towards the sustainability and the affordability of energy, the dependency on the fossil fuel based power plants in the interconnected-power-system can be reduced and more renewable energy based generations can be included. Since the availability of the RE generation is intermittent, the reliability of grid operation becomes questionable with more RE penetration. Hence the reliability analysis in such situation is necessary and the corresponding remedial actions can be proposed to mitigate that stochasticity. More energy storage devices like battery energy storage system, hydrogen storage, pumped hydro storage etc can be incorporated for that purpose. These devices can act both as the load and as the power supplier. The action of the storage system can facilitate the generation-load balance. This in turn can reduce the frequency fluctuation. The whole work can be done in the availability-based-tariff environment and under deregulation.

One more future scope of work can be to incorporate the electric vehicle (EV) in the frequency control scheme so that intermittency occurred due to RE integration can be controlled under ABT regime. In that case the time delay and the non-linearity constraints should be handled carefully with suitably chosen controllers. The controller parameters can be optimized using different newly evolved optimization techniques like brain-emotional-learning-based-intelligent-controller approach (BELBIC), chaotic-optimization-approach (COA), atom search optimization approach (ASO), supply-demand-based-optimization criterion (DSO) etc.

With these future scopes of works derived from this thesis can be explored for better utilization of the RES under application of the unscheduled interchange (UI) price linked frequency control system for interconnected hybrid power system.

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