

LOAD FREQUENCY CONTROL OF WIND INTEGRATED POWER SYSTEMS USING INTELLIGENT CONTROL TECHNIQUES

A dissertation submitted in fulfillment of the requirements for the award of the degree

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in

Power Systems

Submitted by

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DECLARATION

I hereby certify that the work, which is presented in dissertation entitled, “**Load Frequency Control of Wind Integrated Power Systems using Intelligent Control Techniques**” in partial fulfillment of the requirements for the award of the degree of **Master of Engineering in Power Systems**, submitted in Electrical & Instrumentation Engineering Department (EIED), Thapar Institute of Engineering & Technology (TIET), Patiala is an authentic record of my own work carried out under the guidance of **Dr. S.K. Aggarwal, Assistant Professor, EIED**. It refers other researcher's work which are duly listed in the reference section. The matter presented in this dissertation has not been submitted elsewhere for the award of any other degree from any other institution except as reported in text and references.

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ABSTRACT

The load frequency control (LFC) is an important problem to maintain constant frequency of the electric power systems operation. Most LFCs are primarily equipped with integral controllers. The integral gain is set to a level that compromises between fast transient recovery and low overshoot in the dynamic response of the overall system. Moreover, these controllers are slow and do not allow to take in to make changes in operating condition and non-linearity in the generator unit. Doubly Fed Induction Generator (DFIG) based wind turbines run at variable speed, resulting in the variable power generation and also possess non-linearity in the systems. Large frequency deviation due to higher wind power penetration. This puts pressure on thermal and fast response generators (Increased requirements on system flexibility). Moreover, it lacks in robustness. Hence, Artificial Neural Networks (ANN) based controllers can relieve these problems. The proposed study of LFC has implemented ANN based NARMA L₂ controllers on two area wind integrated power systems for simulation to study dynamic response of control areas with different loading condition. The simulation results obtained are satisfactory. The results suggest that ANN based NARMA L₂ provides better control to wind integrated non-linear systems.

Keywords: *Load frequency control (LFC), Proportional-integral (PI) controllers, Doubly fed induction generators (DFIG), Artificial neural network (ANN), NARMA L₂*

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ABBREVIATIONS

AGC	Automatic Generation control
LFC	Load Frequency control
AVR	Automatic Voltage Regulation
ACE	Area Control Error
ANN	Artificial Neural Network
DFIG	Doubly Fed Induction Generator
PI	Proportional-Integral
BP	Back Propagation
NARMA	Non- linear Auto Regressive Moving Average

NOMENCLATURE

ΔP_G	Change in generated power
ΔP_L	Change in power demand
Δf	Change in frequency
T_g	Governor time constant
ΔP_m	Change in mechanical power
ΔP_V	Change in position of valve
T_g	Turbine time constant
ΔP_{12}	Power flow from area1 to area 2
ΔP_{tie}	Change in tie-line power
δ	Power angle
V_1	Terminal voltage of area 1
V_2	Terminal voltage of area 2
β	Frequency bias
T_p	Power system time constant
D	Damping factor

K_i	Integral gain
T_{ij}	Synchronizing torque coefficient of tie line
ΔP_{tie}	Change in tie line power
λ	Tip speed ratio
W_{turb}	Rotor angular velocity
R	Radius of rotor
V_{wind}	Wind velocity
C_p	Power efficiency constant
ρ_{air}	Air density
ΔP_{NC}	Non-conventional power generation
K_p	Proportional gain
M_P	Maximum peak overshoot
t_s	Settling time

CHAPTER 1

INTRODUCTION

1.1 OVERVIEW

Electricity has become an essential need for all. The generated power must be controlled to meet actual power demand with retaining the best quality to get optimal performance from electrical equipment. Now days, the conventional power plants are unable to meet rising demand due to environmental constraints and uncertainty in power demand. It can also be explained as the imbalance between system loads and generated power which reduces power quality causes rapid disturbances in the system. During transmission process, both active as well as reactive power must be balanced between generators and loads. When this balance is violated, the power quality reduces.

Although, both reactive and active powers mutually effects frequency and system voltage. Alternators having two independent control loops Automatic Voltage Control (AGC) and Automatic Voltage Regulation (AVR) to control frequency and voltage fluctuations respectively. Load Frequency Control (LFC) is an important function of AGC used to control frequency deviation with the active power control while, AVR is used to regulate terminal voltage with reactive power control. There are two functions of LFC, firstly to maintain frequency constant and secondly to regulate error of tie-line power exchange following a load variation in an interconnected system [1].

Several control techniques are proposed by the authors by their research work design LFC controllers. These controllers are categorized as follows

- 1) Classical controllers
 - a) Linear Quadratic Regulator (LQR) controller
 - b) Proportional Integral (PI) controllers
 - c) Proportional Integral Derivative (PID) controllers
- 2) Artificial intelligence based controllers
 - a) Fuzzy logic
 - b) Generic algorithm (GA)
 - c) Artificial neural network (ANN)

Over a decade, Proportional-Integral (PI) controllers are used in most of the industries as conventional frequency controllers. Several controlling methods had been applied to find optimal values of the gains of PI controllers. Among them Bode plot, Ziegler-Nichols technique is the simplest experimental method to find the optimal value of gains proportional (k_p) and integral (k_i) to control optimization problem.

Recently, penetration of Renewable Energy Sources (RES) has risen globally. With the rising needs and advantages RES, it's beneficial to integrate it with conventional power generators. The issues like, depletion of fuels, global warming emissions, destruction of wildlife, rising pollution level, etc. can be resolved by the integration of renewable sources. RES consisting mainly solar, wind, tidal and geothermal energy, among all these wind power is cleanest, reliable and sustainable source to generate electric power. The major issue present in the integration of these resources is the frequency and voltage mismatch of these resources with the main grid.

While it is the complex task to control the frequency deviation in case of renewable source integrated system. Previously, the conventional controllers are used to control frequency deviation. After the introduction of renewable power generators it becomes quite complex to control active power generation and frequency change. The renewable generators such as wind turbines produce variable power which is proportional to the turbine blade speed which produces uncertainty in power generation [3].

Therefore, artificial neural network (ANN) based controllers are introduced to frequency control problem to regulate power generation against the variable demand. The ANN controllers with advance adaptive control structure is robust to control the non-linearity in power generation and enhancing power quality, system stability with narrow frequency change in the power system [4].

In this dissertation work, ANN based NARMA L2 controller has been preferably adapted to control frequency oscillations and tie-line power flow. NARMA L2 controller is relatively faster control than other controllers. The controller has been trained to control two areas interconnected DFIG wind penetrated system. Transient response due to sudden change in load is compared with conventional PI and NARMA L2 controllers.

1.2 Literature Review

The load frequency control is the vast area of research in the operational power system. In recent times intelligent control methods are conquering over PI controller, which was used as a conventional controller in most industrial applications to control frequency problems. The optimized tuning of these intelligent controllers with renewable penetration and non-linearity has been done using many techniques and algorithms in huge numbers of journals and research articles which is being discussed in this section.

Elgerd and Fosha [5] was first to suggest the optimum frequency governor of two area power system. Both the identical control areas equipped with non-reheat steam turbines for the construction of load frequency control model. They also presented optimal multi area active power and frequency control. The American Power Systems Committee mentions that frequency bias for each control area should be set equal to the so-called area frequency response characteristic (AFRC). But the committee failed to explain basis for this practice and author, suggested and proved by the methods of optimal control that provides better results and broader stability margins that can be obtained by setting slower bias.

Fosha and Elgerd [6] discussed about the expansion of a state variable model of multi area load frequency problems. The utilization of mathematical equations was necessary for the implementation of advance control scheme. It also discussed about the feedback controller, which was quite effective in terms of construction in comparison to the previously designed controller. The result shows the productive ways for improving the dynamic response as well as stability limitations of load frequency control system.

Bunker *et al.* [7] discussed about the effect of instantaneous variations in the wind power over the system operation whenever the components were further decomposed into slow, fast and ramp components. The long term simulation model proves that variations in the wind power affect the normal operation of power system on a smaller side. Still, there was also a threat of a random increase in wind power as well as power demand that can further overlap the remaining capability of the complete system. It also discussed about the various wind related methodologies and the control area performance that can further help by linking the main grid with the rest of the system.

Lei *et al.* [8] discussed about the implementation of a proposed DFIG wind model having a power converter as the controlled voltage source for regulating the flow of rotor current to

achieve the desired real and reactive power. This model had a form of conventionally proposed generator model that can further utilized as the power simulation tool such as PSS/E. To verify the effectiveness of the proposed model, it was compared with the desired model designed by Dig silent. The drawbacks as well as the merits of the proposed model were also displayed for the better performance of the model in comparison to previously designed alternatives.

Muljadi *et al.* [9] discussed about the utilization of variable speed wind turbine for the effective pitch control. It also discussed about the controlling scheme for the system to minimize the load and at the same time maximizing the energy for the better performance.. During the period of low speed till the medium speed, the effective controlling of the wind turbine could be done for the utilization of maximum energy from the wind by the combination of generator and the converter site. During the period of high speed, the turbine was controlled in a well-mannered to maintain the aerodynamic power. For the effective controlling, generator load control and the pitch control were utilized. The working of both the scheme was to control operating region of the wind turbine. The results showed the effectiveness of the scheme for minimizing the load at the same time maximizing the energy over a wide speed region.

DE Almeida *et al.* [10] discussed about the control scheme that can further utilized by the induction fed generator for its effective participation in the frequency regulation of the system. On the basis of proposed control scheme, the wind generators worked according to the extraction curve in such a manner that the increment or decrement in the wind power completely depends upon the unwanted variations in the frequency of the system.

Lalor *et al.* [11] discussed about the effect of unwanted variations in the wind cause deviation in the frequency control over the Ireland electricity system. It also discussed about the various topologies related to the wind generations. The effective wind generation system was also presented and its effect over the frequency control of increasing wind generation was also reviewed here. And the various opportunities related to the additional control of wind generation were also discussed.

Johan Morren *et al.* [12] discussed about the utilization of wind farms for the frequency control which was quite a revolutionary way for the effective control, but it was difficult to utilize them as an energy source as they could not be controlled directly. Till now, there was

only a single method that can fulfill this requirement in which wind turbine was not providing maximum power due to which some margin was left. As discussed about the previously designed generator, the kinetic energy was also stored in the rotating mass of the blades of wind turbines. It also discussed about the value of inertia that was not displayed yet, but very helpful for the grid. Due to this, for the short interval of time the inertia of a wind turbine and the frequency control of the turbine can easily match with the grid.

Bevrani H. et al. [13] discussed about the one of the major challenges of frequency regulation in the interconnected two area network by wind turbine in today's world. The major issue of power imbalance and the frequency deviation arise due to unwanted fluctuations in wind power. It also discussed about the effective agent based on LFC for the multi-area power system using multi-agent reinforcement learning (MARL). The simulation was done on a standard 39 bus system to prove the effectiveness of the proposed technique.

Sinha S.K. et al. [14] discussed about the AGC of two-area interconnected power system. The continuous deviation was seen in the frequency and the tie line power again and again with respect to time due to unwanted variation in the load needed to be minimized by the utilization of various controllers to improve the system efficiency. Due to these variations, an effective controller was designed. An addition to this controller, integral controller was also designed in this research work as well as it was further compared with the previously designed controller. The results showed the effectiveness of the proposed controller in comparison to integral controller in terms of better performance as well as settling time.

Bevrani et al. [15] discussed about fuzzy logic tuned PI control technique. For instantaneous control of frequency change and tie-line power which is essential for smooth run in the presence of high wind penetrated system. PSO technique has been amplified parameters of membership functions.

Janaka Ekanayake et al. [16] present concept of an extra control loop connected to a DFIG based wind turbine to back up the inertia response by discharging the kinetic energy of the turbine when frequency of power generator decreases. The paper shows that large changes in rotor speed in DFIG is forced to high regulation of the frequency. The extra reference power from the DFIG wind turbine is obtained by rate of change of frequency and network inertia. This extra power from the wind turbine participates in primary frequency control and hence avoids system inertia to shrink.

Liu Xiangjie *et al.* [17] discussed about the utilization of predictive algorithm for the LFC in order to improve the overall efficiency of the system. It also discussed about the generation rate constraints. By the utilization of the generalized predictive algorithm for the LFC in order to build Controlled Auto-Regressive Integrated Moving Average model (CARIMA). The obtained results verify the feasibility of the proposed algorithm for the load frequency control.

B. Franoise *et al.* [18] discussed about the utilization of layered neural network in the non-linear control of the complete system. It also discussed about the feed forward neural network controller for its implementation within the two area system that can further minimise the variation in the frequency as well as produce zero steady state frequency error. Results showed the training of the controller with the help of back propagation by the implementation of time algorithm.

A.P. Birch *et al.* [19] discussed about the utilization of neural network in the standard predictive LFC. It also discussed about the benefits of proposed control scheme over the conventional schemes. The results verify the effectiveness of the proposed technique that can further improved the overall efficiency of the system.

D. K. chaturvedi *et al.* [20] discussed about the implementation of nonlinear neural network with the help of generalised neural network. Is also discussed about the various demerits of the conventional schemes that were overcome by the proposed scheme that can further help in the minimization of unwanted frequency variations and at last the performance as well as the system stability also improved.

A. Demiroren *et al.* [21] discussed about the utilization of artificial neural network for its implementation in the AGC of the two area system. It also discussed about the effect of computer simulation in the interconnected two area system that further includes the effect of various parameters such as re-heater effect as well as governor dead band effect, the results obtained verify the effectiveness of the ANN control scheme for damping out oscillation in the case of load fluctuation.

H. Shayeghi *et al.* [22] discussed about the utilization of non-linear ANN controller that completely depends upon the AGC of the power system. The simulation result showed the implementation of the proposed controller, which was quite effective as well as having

improved performance in the case of GRCs. It also showed the effectiveness of the proposed controller in comparison to conventional PI controller.

A. Demiroren *et al.* [23] discussed about the implementation of layered ANN controller for the minimization of problems related LFC in the power system. It also discussed about the proposed control scheme having three interconnected areas with the two thermal and one hydro area. The results show better performance of the proposed controller in comparison to the conventional controllers.

K. P. Wong [24] discussed about the implementation of artificial intelligence in the various neural related applications. It also discussed about the application of artificial intelligence in the power system. It also discussed about the artificial intelligence technique which was further employed for the various applications of the conventional artificial tools.

Wei Zhang *et al.* [25] suggested strategy for coordinated control of wind turbine to participate in LFC problems. A system is designed for coordinated control in order to enable the wind turbine to participate in multi- area LFC problem. The designed control scheme is verified to be stable with system non-linearity and load change. To design wind generated model, the coordinated unloading scheme is used to track active power demand from the system response. The coordinated control strategy can achieve fast response under load change without including pitch angle control of wind turbines. The effectiveness is studied through simulation of designing systems.

D. C. Prowse [26] discussed about the utilization of the AGC simulation program and the implementation of nonlinear Optimization logic that can further help in the development of ACE filter algorithms. The results showed the effectiveness of the proposed technique by reducing the amount of control action and also help in the improvement of control performance.

1.3 MOTIVATION

The conventional power plants are unable to fulfil rising demand due to economic and environmental constraints. Recently with the rising needs and the advantages of RES the penetration of renewables has raised. After 1990s, the generation of electric power through wind turbines developed and rapidly increasing in recent years. India comes on the fourth position beneath Denmark and the USA in terms of wind power generation capacity. But the

growth rate of India is higher among them. The modern power system has been highly penetrated with wind turbines (WTs). But due to variable nature power generation participation of WTs in primary frequency control is limited. Moreover, PI controllers may not be able to control frequency oscillations in renewable penetrated power system following load disturbances.

Therefore, intelligent techniques are introduced to control the real power and change in frequency with less complexity of wind integrated non-linear system. The main motivation behind this work to study the dynamic performance of neural network based NARMA L2 controller in the wind penetrated system following a load disturbance and participating in primary frequency control.

1.4 OBJECTIVES

1. To develop Simulink model of two area interconnected systems that consists of renewable energy source
2. To design the PI and NARMA L2 controller in order to regulate the frequency following a load disturbance
3. Analyse performance of ANN based controllers under high wind penetration and system non-linearity.
4. To compare the performance of two controllers in terms of settling time, overshoot and undershoot.

1.5 ORGANIZATION OF THE THESIS

- | | |
|-----------|---|
| Chapter 1 | This gives the overview of the proposed work, motivation, literature survey, objective, and scope of work and the organization of the thesis. |
| Chapter 2 | Here it gives the overview on the AGC and the description of the each part of the power system. |
| Chapter 3 | It explains intelligent control techniques. It gives the brief of ANN based NARMA L2 Controller. |
| Chapter 4 | It includes the simulation and the results obtained by the each controller. |
| Chapter 5 | Provides the conclusion and the future scope of the proposed work. |

CHAPTER 2

POWER SYSTEM MATHEMATICAL MODELLING

A typical power system model is described in this chapter having generating units, tie- lines and power system loads. Generators are used to generate electric power from natural sources, transmission lines transmit bulk power from generating units to power loads and distribution system supplies electric power to different loads. The power system load keeps on changing and causes perturbation which leads to instability and even blackouts in serious cases. Study response to load change is needed to overcome this problem using mathematical model and Simulink. Mathematical model of load change is obtained by the linearizing system for real time operating point. But non- linear differential equation have to be solved for large disturbance. LFC basically depends on small signal analysis. The linearized models of governor, turbine, and power system are discussed below which are used frequently for modelling isolated and interconnected systems.

2.1 GENERATING UNITS

A generator of conventional power plants used to transform mechanical or chemical energy into electrical energy. Thermal power plants consisting numbers of control valves to control the steam flow, turbine speed control in order to produce accurate power as per demand.

2.1.1 Governor model

Governor is used to govern the speed of the power generating machine by setting up a reference set value ω_{ref} which is compared to the value of speed sensor ω to give the error in speed $\Delta\omega$. The load keeps on varying as per power demand. The power produced by generator can also be varied by changing the set value of speed governor following load change while maintaining the system frequency constant. The gap between power generated and scheduled power is fed back through droop R [1]. The block diagram of the speed governing system is shown in Fig. 2.1

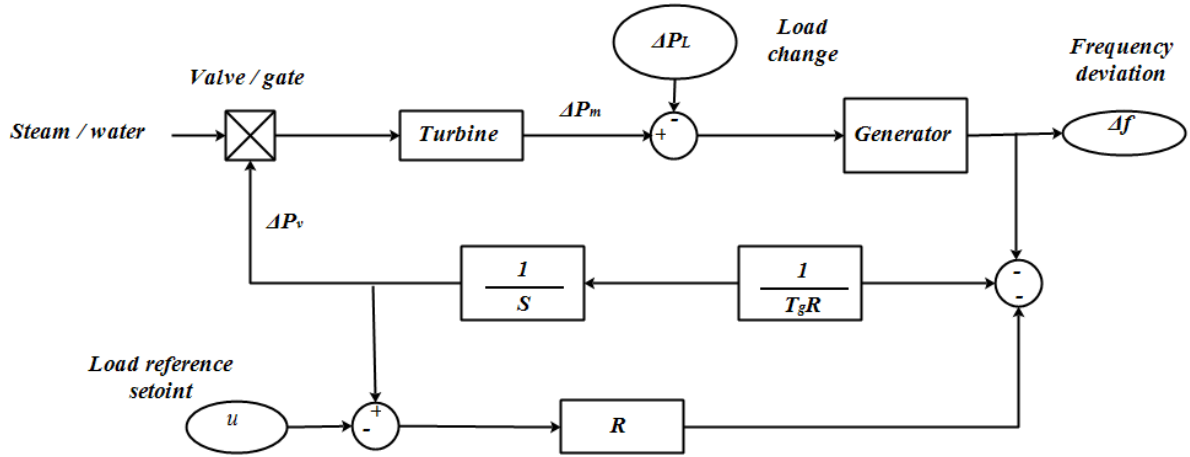


Fig 2.1: Block diagram of speed governing system [1]

The response of governor is given by

$$\Delta P_g = \Delta P_c - \frac{1}{R} \Delta f \quad (2.1)$$

Taking Laplace transform of equation (2.1)

$$\Delta P_g(s) = \Delta P_c(s) - \frac{1}{R} \Delta F(s) \quad (2.2)$$

Transfer function of speed governor is given by

$$T_g(s) = \frac{\Delta P_v(s)}{\Delta P_g(s)} \quad (2.3)$$

$$T_g(s) = \frac{1}{1 + sT_g} \quad (2.4)$$

The overall transfer function of speed governor is shown in fig 2.2

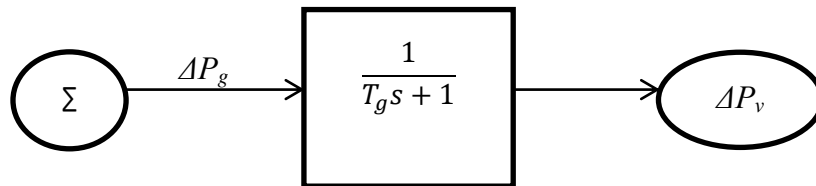


Fig 2.2: Transfer function of governor

2.1.2 Turbine model

The turbine is a prime mover that extracts energy from the steam and converts it to the mechanical power ΔP_m which is further forwarded to the generator. The generator is operated through the turbine. The non-reheat turbine is fundamental which generate power proportional to the opening of the valve. The symmetry between electromechanical air gap powers is maintained by the prime mover for balancing the frequency. If difference between both powers ($\Delta P_T - \Delta P_G$) is positive, then the generator will speed upon the other hand it retarded. Rise in turbine power depends on the load fluctuation connected to the generator. The overall transfer function of non-reheat thermal turbine is given by equation 2.5[1].

$$T_{tr}(s) = \frac{\Delta P_m(s)}{\Delta P_v(s)} = \frac{1}{T_{tr}s + 1} \quad (2.5)$$

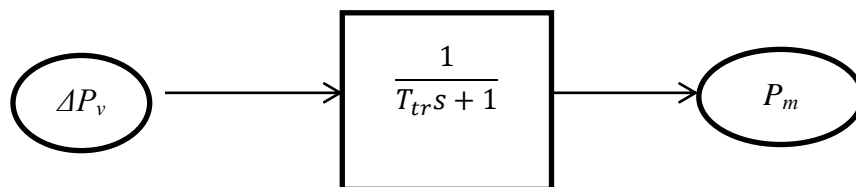


Fig 2.3: Transfer function of turbine

2.1.3 Generator and load model

The generator converts the output of turbine power, i.e. the mechanical to electrical energy, but maintaining rotor speed is more important to keep constant frequency compared to energy conversion. The storage of electrical energy is difficult and uneconomical; therefore generation and the load must be matched. As immediately loads vary, there is a mismatch between the power generated and the electrical load. Most lighting loads are resistive whereas, rotating machine loads are a mixture of resistive and inductive components which are a prominent part of load of the power system. The increase in generating power depends on load change. The increment of generator power ΔP_G changes with ΔP_L . The generator output is always regulated to maintain balance with load change [1].

$$\Delta P_G = \Delta P_L \quad (2.6)$$

Some assumptions were carried out to supply power to the load by the generator:

1. During normal power balance condition, the system runs normally at frequency f^θ .

2. The load change ΔP_L occur in the system, and then generation must be increased to fulfil raising demand *i.e.* $\Delta P_G = \Delta P_L$.
3. The kinetic energy is proportional to the square of speed; therefore the equation for kinetic energy is given by

$$P_{12} = \frac{|V_1||V_2|}{X} \sin(\delta_1^0 - \delta_2^0) \delta_1^0 \delta_2^0 \quad (2.7)$$

4. With a change in motor load, frequency fluctuates as it is sensitive to rotor speed. Such that the rates of load change with respect to frequency variation is constant.

$$D = \frac{\partial P_L}{\partial f} \quad (2.8)$$

From balance power equation,

$$\Delta P_T = \Delta P_L + \frac{d(W_{kin})}{dt} + \beta \Delta f \quad (2.9)$$

Since,

$$f = f^0 + \Delta f \quad (2.10)$$

Equation of kinetic energy after neglecting Δf will be written as

$$W_{kin} = W_{kin}^0 \left[1 + \frac{2\Delta f}{f^0} + \left(\frac{f}{f^0} \right)^2 \right] \approx W_{kin}^0 \left[1 + 2 \frac{\Delta f}{f^0} \right] \quad (2.11)$$

$$\Delta P_T - \Delta P_L = \frac{2W_{kin}^0}{f^0} \frac{d}{dt}(\Delta f) + \beta \Delta f \quad (2.12)$$

Kinetic energy stored at specified frequency is

$$W_{kin}^0 = H \times P_r \quad (2.13)$$

Dividing the eqn. by P_r

$$\Delta P_T - \Delta P_L = \frac{2H}{f^0} \frac{d}{dt}(\Delta f) + \beta \Delta f \quad (2.14)$$

The advantage of variable H is independent to size of system. The equation (2.14) can be rewritten as

$$\Delta P_T - \Delta P_L = 2H \frac{d}{dt} \left(\frac{\Delta f}{f^0} \right) + \beta f^0 \left(\frac{\Delta f}{f^0} \right) \quad (2.15)$$

Laplace transform of (2.6)

$$\Delta P_T(s) - \Delta P_L(s) = \frac{2H}{f^0} s \Delta f(s) + \beta \Delta f(s) \quad (2.16)$$

Hence, Laplace transformation of change in frequency is given by

$$\Delta f(s) = G_p(s) [\Delta P_T(s) - \Delta P_L(s)] \quad (2.17)$$

Where,

$$G_p(s) = \frac{K_p}{1 + sT_p} \quad T_p = \frac{2H}{\beta f^0}, \text{ and } K_p = \frac{1}{\beta}$$

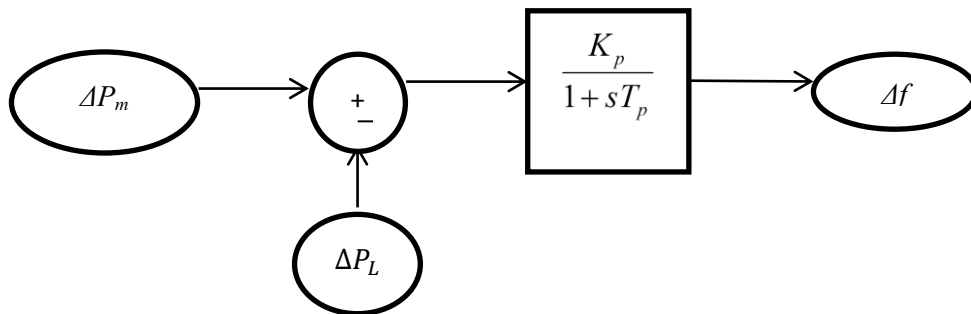


Fig2.4: Block diagram of generator and system load

To study the overall dynamic performance of the all the components for steady state analysis of the systems all the transfer function blocks are combined to generate a control system.

2.2 SINGLE AREA SYSTEM

The combination of all the above transfer system block diagrams gives the single area system. When a coherent group of generators feeding the localized load with isolation to another group is known as a control area.

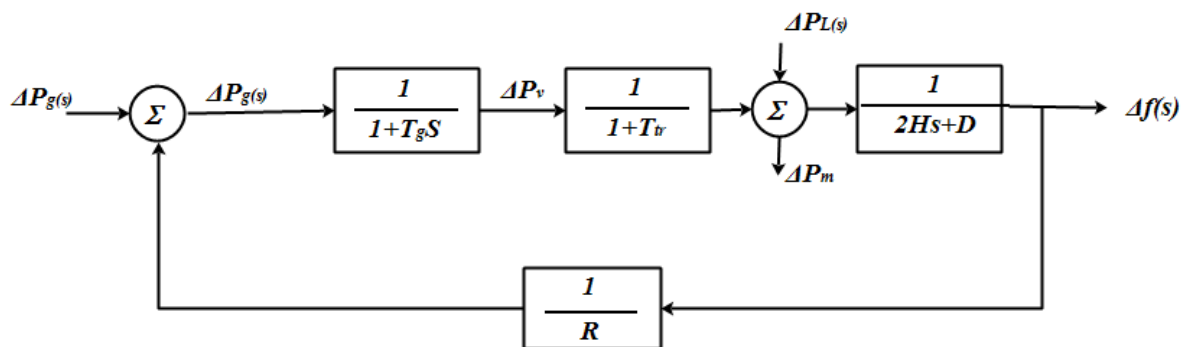


Fig 2.5: Block diagram of single area isolated power system with primary control loop

2.2.1 AGC in single area systems

AGC problem has been distributed into three categories primary, secondary and tertiary control loop. The primary and secondary loops combined to LFC, economic dispatch comes under tertiary control.

Primary loop gives power generation proportional to the derivative of frequency, it stabilize system changing reference frequency. As the load changes, frequency of the system deviates. To reduce this deviation to zero, we must reset reference signal using an integral controller as a secondary control loop. Secondary control loop rise system type by 1 which reduce the output frequency deviation to zero [2].

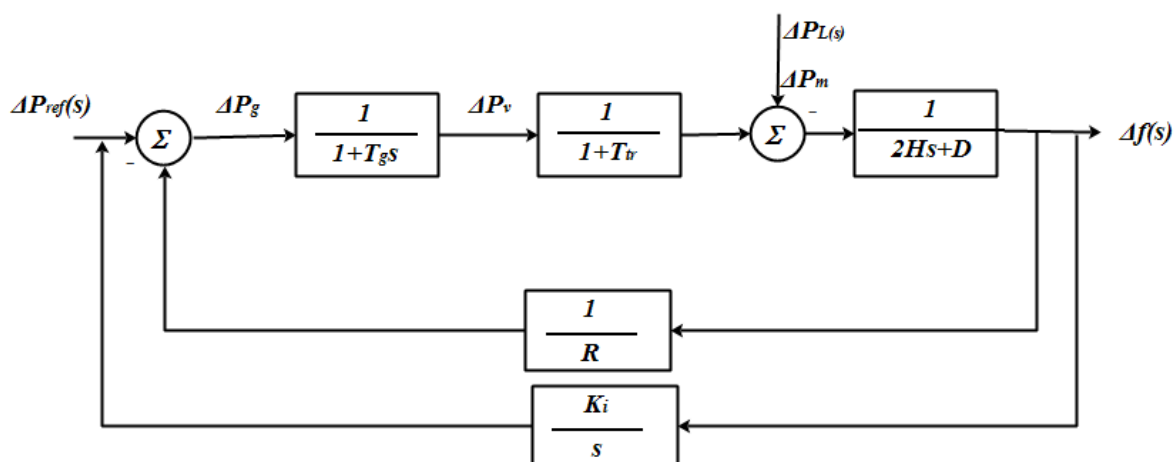


Fig 2.6: Block diagram of an isolated power system with primary and secondary control loop

2.3 TWO AREA INTERCONNECTED SYSTEM

In single area system the local generators are insufficient to feed continuously deviating load which leads to change in frequency of the system. The excess frequency drop leads to system insecurity. Therefore, two or more control areas are connected through tie-lines to exchange the power between two or more control areas through transmission line or conductors [2].

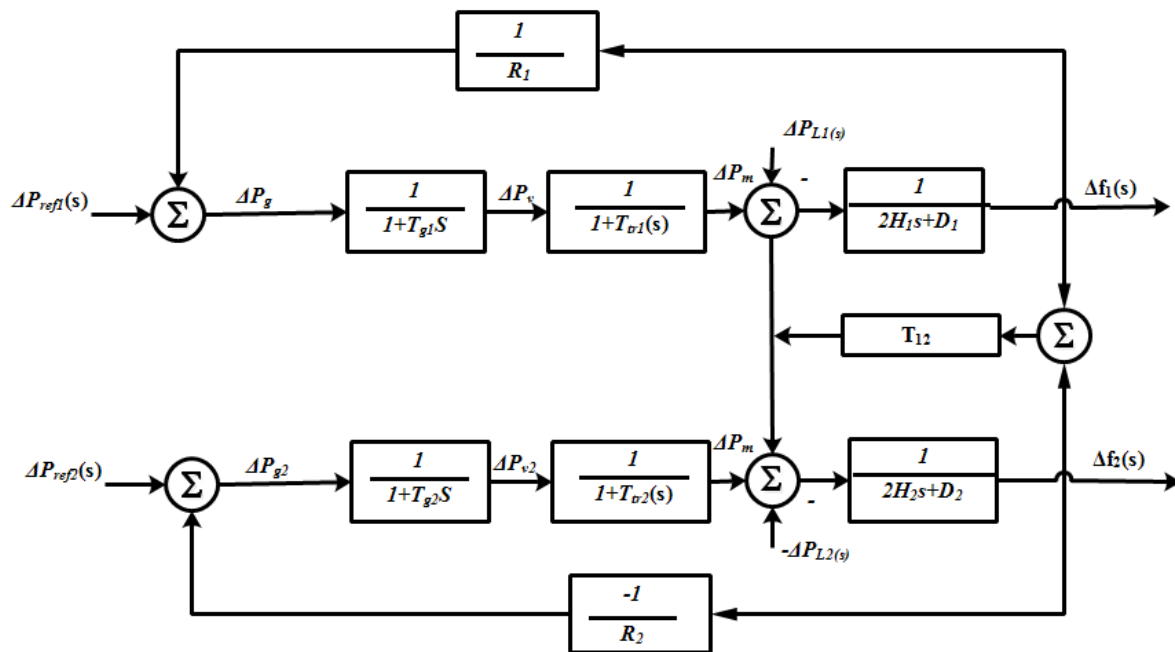


Fig 2.7: Block diagram of two areas interconnected power system with primary control loop

2.3.1 Tie-lines

Tie-lines are basically the long transmission lines connecting two or more generation units. The tie lines are used to connect two more coherent group of generators situated at different control areas of interconnected systems. The tie lines also share power from surplus areas too deficient to maintain the balance between generation and demand and also it narrows frequency deviation.

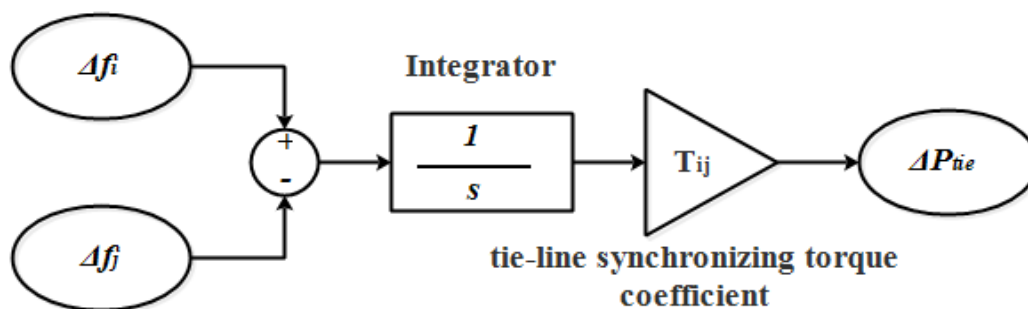


Fig 2.8: Transfer function of tie-lines

$$P_{12}^0 = \frac{|V_1||V_2|}{X} \sin(\delta_1^0 - \delta_2^0) \quad (2.18)$$

Where, δ_1^0, δ_2^0 = power angles of coherent machines

$$\Delta P_{12} = T_{12} (\delta_1 - \delta_2) \quad (2.19)$$

Where
$$T_{12} = \frac{|V_1||V_2|}{X} \cos(\delta_1^0 - \delta_2^0) \quad (2.20)$$

$$\Delta f = \frac{1}{2\pi} \frac{d}{dt} (\delta^0 - \Delta\delta) = \frac{1}{2\pi} \frac{d}{dt} (\Delta\delta) \quad (2.21)$$

And
$$\Delta\delta = 2\pi \int \Delta f dt \quad (2.22)$$

$$\Delta P_{12} = 2\pi T_{12} \left(\int \Delta f_1 dt - \int \Delta f_2 dt \right) \quad (2.23)$$

Hence
$$\Delta P_{12} = \frac{2\pi T_{12}}{s} (\Delta f_1(s) - \Delta f_2(s)) \quad (2.24)$$

2.4 AREA CONTROL ERROR

Area control error (ACE) of an area is given by addition of error in frequency and power through tie line. ACE represents mismatching between loads and generation of two areas. The purpose of load frequency control is to shrink the error in the frequency of both areas as well as to remain error in the tie line power to preferred value which is not an easy task because of fluctuating load. The error in frequency ought to maintain at zero and the steady state errors within the frequency of the power system is that the outcome in error in tie-line power as a result of the tie line power error is that the integral of the frequency variation between each area.

$$ACE_i = \sum_{j=1}^n \Delta P_{tie,ij} + \beta_i \Delta f_i \quad (2.25)$$

$$\beta_i = \frac{1}{R_i} + D_i \quad (2.26)$$

2.5 WIND POWER GENERATION

2.5.1 Wind turbines technology

Classification of wind turbines was done on the principle of energy conversion, i.e. aerodynamic drag and aerodynamic lift. Modern wind turbines convert energy on the principle of aerodynamic lift. The blades of these turbines directly interact with wind blowing at moderate speed which results, drag force in the direction of wind. Another force perpendicular to the drag is called lift force which is several times larger than the drag force which is responsible for rotor movement. There are two types of aerodynamical lift based turbines based on spin axis orientation. [28]

- i. Horizontal axis turbine
- ii. Vertical axis turbine

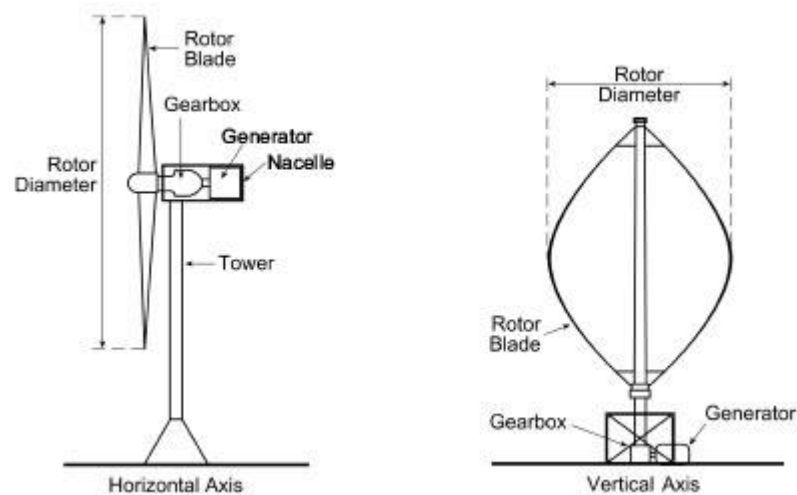


Fig 2.9: Horizontal and vertical axis wind turbines [28]

The main shaft of the rotor in the vertical axis turbine is set vertically. In these turbines there is an advantage to place generators and gearboxes near to the ground. The horizontal axis turbines are widely used for industrial purpose. In these turbines axis of the rotation of the rotor are parallel to wind blow and surface of the ground. The wind blowing through both surface air foil shaped blade, but speed is faster through upper side and slower through the lower side of the air foil which creates a low pressure area above air foil with respect to below. The difference in pressure between the top and bottom surface is called aerodynamic lift. The turbine blades are fixed to move in a plane with considering hub as centre, such that rotation about hub is caused due to lift force, apart from lift force a drag force. It consists

nacelle mounted over a tower generator, gearbox and the rotor. In case of small wind turbines tail vanes are for orientation of the rotor and nacelle into the wind while mostly horizontal axis turbines carry two or three blades or even more blades. The number of blades is depending upon Tip Speed Ratio (TSR) is defined as the division of blade tip speed by speed of wind. TSR is denoted by λ which is given by the equation

$$\lambda = \frac{\omega_{turb} R}{V_{turb}} \quad (2.27)$$

It is important to adjust the tip speed ratio, so that power extracted will be close maximum while operating turbine at variable speed. The turbulence is created in the path as air passes through rotor blade. If the next rotor blade comes under the effect of turbulence, the power is not extracted properly. However, if the rotor speed gets slower, there will be no effect of turbulence in the air to the blades. Therefore TSR should be optimized to reduce the effect of turbulence.

The number of blades in wind turbine gives the optimized TSR. If the number of blades are less the faster the wind turbine rotor responsible for maximum power extraction from wind. The optimum of TSR of 2 bladed rotors is nearly 8, three- bladed turbine nearly 5, a four bladed rotor nearly 3. The tip speed ratio of a properly designed typical three bladed rotor is between 6 to 7.

2.5.2 Power from wind

The rotor characteristics of the turbine can be obtained by the relation between the overall wind power and mechanical power absorbed by turbine blades from wind. These relations are eagerly referred initialize with wind absorbed inside rotor swept area. It is clear that the kinetic energy of air cylinder with radius drifting at speed of wind V_{wind} gives over-all wind power P_{wind} within the area swept by the rotor of the wind turbine. The equation for wind power can be expressed as given in equation (2.28) [29]

$$P_{wind} = \frac{1}{2} C_p \rho_{air} \pi R^2 V_{wind}^3 \quad (2.28)$$

It is practically impossible to extract all the kinetic energy from the wind. This would not allow the air to pass through the wind turbine, which is almost unachievable condition. The wind turbine reduces speed of wind, which thus extracts a fraction of the power in the wind. This fraction is expressed as the power efficiency coefficient (C_p), of the wind turbine.

Therefore the mechanical power output of the wind turbine P_{mech} considering the definition of C_p can be given by (equation 2.29) and (equation 2.30) [29],

$$P_{mech} = C_p P_{wind} \quad (2.29)$$

$$P_{mech} = \frac{1}{2} C_p \rho_{air} \pi R^2 V_{wind}^3 \quad (2.30)$$

The maximum theoretical static limit of C_p is $16/27$ (0.593 approx.) which is maximum possible value i.e. 59 % of power can be extracted from kinetic energy of wind. It is also called as Betz Limit. Practically mechanical power extracted P_{mech} depends upon rotor speed, wind speed, and blade angle. Hence, P_{mech} and C_p are functions of these parameters (eqn. 2.31)

$$P_{mech} = f(\omega_{turb}, V_{turb}, \beta) \quad (2.31)$$

2.5.3 Participation of DFIG-based wind turbines in single-area LFC problem

Basically, conventional generation units are deputed to perform AGC and frequency regulation task with the help of primary and secondary control of the governor. Practically, constant speed wind turbines do not take part in frequency control. Hence, the power generated by wind turbines is independent of system loading change. They do not contribute to system inertia.

To increase and development in wind power capacity, its contribution to share load has increased, but to participate in frequency control its system inertia reducing to its adequate level following load change. Hence, the participation of wind generators through penetrated wind power is required and system demand. In order to restrict decline of total system inertia. Extracting power from variable speed wind generator becomes the key solution to overcome this problem.

Earlier traditional constant speed wind turbines are not allowed to supply maximum available power in normal condition because they have to maintain reserve margin which can be utilized for frequency control [31]. Recently, some researches in this field of extracting power from a variable speed wind turbine have been done.

For the control system based power DFIG (Doubly Fed Induction Generator) based wind turbine is used to extract power with variable mechanical speed and for supporting primary

frequency regulation kinetic energy is extracted which are based on wind turbine inertia control model [30]. Block diagram of such control system is shown in figure 2.10

DFIG based machines equipped with slip ring rotors and commonly designed with 3 AC windings in the stator and rotor. The stator is directly connected to the grid and power to the rotor is supplied through frequency converter. Thus the equation of stator rotating field can be given as

$$\frac{\omega_s}{P_s} = \omega_{mech} \pm \frac{\omega_r}{P_r} \quad (2.32)$$

In figure 2.10 P_s and P_r represents the number of poles of the stator and rotor respectively. Here, the system frequency ω_s is given by the addition of rotor current frequency and angular velocity of mechanical rotation. These types of machines can operate under or over synchronous speed depending upon the direction of supply frequency when the speed of the machine is reduced the amount of kinetic energy release from the shaft is given by ΔE_k as expressed in equation (2.35) below

$$E_{k0} = \frac{1}{2} J \omega_{mech0}^2 \quad (2.33)$$

$$E_{k0} = \frac{1}{2} J \omega_{mech0}^2 - J \omega_{mech1}^2 \quad (2.34)$$

$$\Delta E_k = E_{k0} \left(1 - \frac{\omega_{mech1}^2}{\omega_{mech0}^2} \right) \quad (2.35)$$

E_{k0} depends on speed of wind, which varies between 0 to 1 per unit and mechanical rotational speed ω_{mech} cannot be smaller than minimum value of speed of the DFIG based wind turbine. Also, instantaneous extracted power should not exceed the maximum limit from a rating of the machine. These constraints are employed in control system and expressed as an equation (2.36)

$$E_{k0} = f(\text{windspeed}) \quad (2.36)$$

$$0 \leq E_{k0} \leq 1 = f(\text{windspeed}) \quad (2.37)$$

$$\omega_{mech_{min}}^2 \leq \omega_{mech1} \quad (2.38)$$

$$E_{k0} + \Delta E_k \leq E_{k_{max}} \quad (2.39)$$

As shown in Fig. 2.10 to operate the turbine at its optimum speed to produce the maximum power control scheme have been explained. The reference point in the controller (P_ω) is set which depend on measured speed ($\omega_{m_{meas}}$) and electric power ($P_{el_{meas}}$). The reference value act as input signal to converter control gives power and torque by rotor current control of generator. Another control signal (ΔP_f) which adapt the reference power as derivative function and change in grid frequency per unit time. The inertia calculated through additional control system is proportional to its control parameters (K_{df} and K_{pf}). As the system frequency falls the reference value of torque is increased, rotor speed decreases and hence kinetic energy is released.

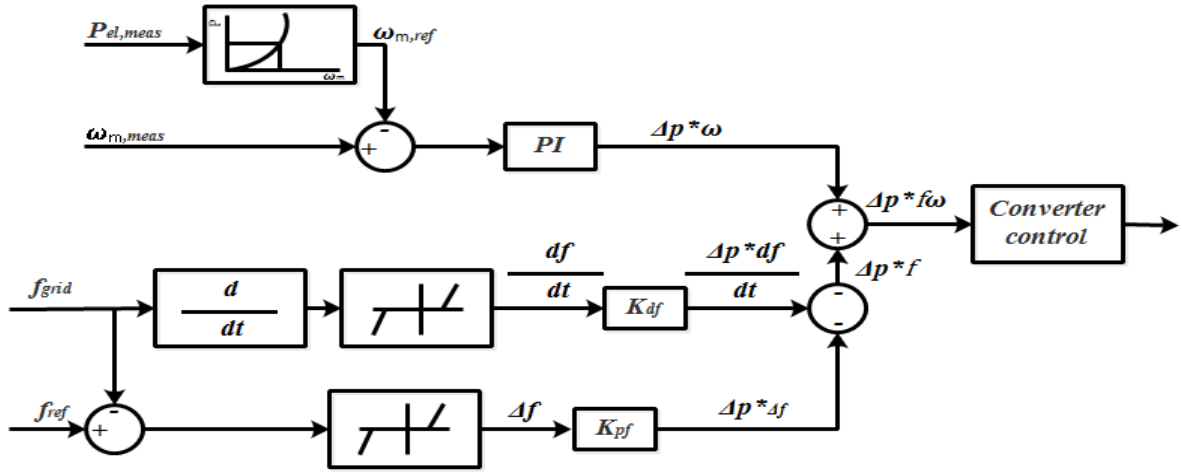


Fig 2.10: Principle of DFIG Inertial Emulation Control

There are two components of reference power (ΔP_ω) and another reference value (ΔP_f) depend on frequency change and (ΔP_ω) which depend on speed of turbine as a function of wind speed as given by equation (2.40)

$$\Delta P_f^* = -K_{df} \frac{df}{dt} - K_{pf} \Delta f \quad (2.40)$$

$$\Delta P_\omega^* = -K_{wp} (\omega^* - \omega) + K_{wi} \int (\omega^* - \omega) dt \quad (2.41)$$

$$\Delta P_{f\omega}^* = \Delta P_f^* + \Delta P_\omega^* \quad (2.42)$$

For PI controller gains are (K_{df} and K_{pf}) two components of wind turbine taken as reference. (ΔP_{ω}) is relatively slow whereas (ΔP_f) fast. Therefore when change in load occurs we consider (ΔP_{ω}) to be zero. Also consider the sudden load change of set points to power by converter, we could assume ($\Delta P_{NC} = \Delta P_{f\omega}$)

$$\Delta P_{f\omega}^* = \Delta P_f^* \quad (2.43)$$

$$\Delta P_{NC} = \Delta P_{f\omega}^* = \Delta P_f^* = -K_{df} \frac{df}{dt} - K_{pf} \Delta f \quad (2.44)$$

2.5.4 DFIG-based wind turbine control model

Figure 2.11 shows the overall transfer function block diagram of power system consisting conventional as well as non-conventional generators. Both generators are participating in frequency control. The incremental load change active power demand (ΔP_D) is subtracted from total generation by thermal as well as wind (ΔP_{NC}) gives the value of power exported from the neighbouring area which can be expressed by equation 2.45

$$\Delta P_g + \Delta P_{NC} - \Delta P_{12} - \Delta P_D = \Delta P_f \quad (2.45)$$

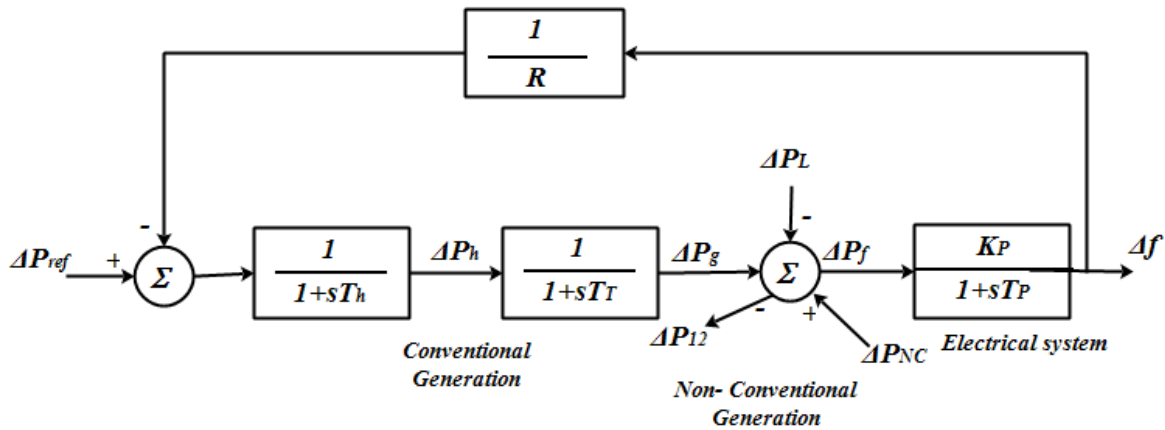


Fig 2.11: Dynamic model of power system with hybrid generators

$$T_p = \frac{2H}{fD} \quad (2.46)$$

$$K_p = \frac{1}{D} \quad (2.47)$$

$$\frac{2H}{f} \frac{d\Delta f}{dt} = \Delta P_f - D\Delta f = \Delta P_g + \Delta P_{NC} - \Delta P_{12} - \Delta P_D - D\Delta f \quad (2.48)$$

$$\left(\frac{2H}{f} + K_{df} \right) \frac{d\Delta f}{dt} = \Delta P_g - \Delta P_{12} - \Delta P_D - \Delta (K_{pf} + D) \quad (2.49)$$

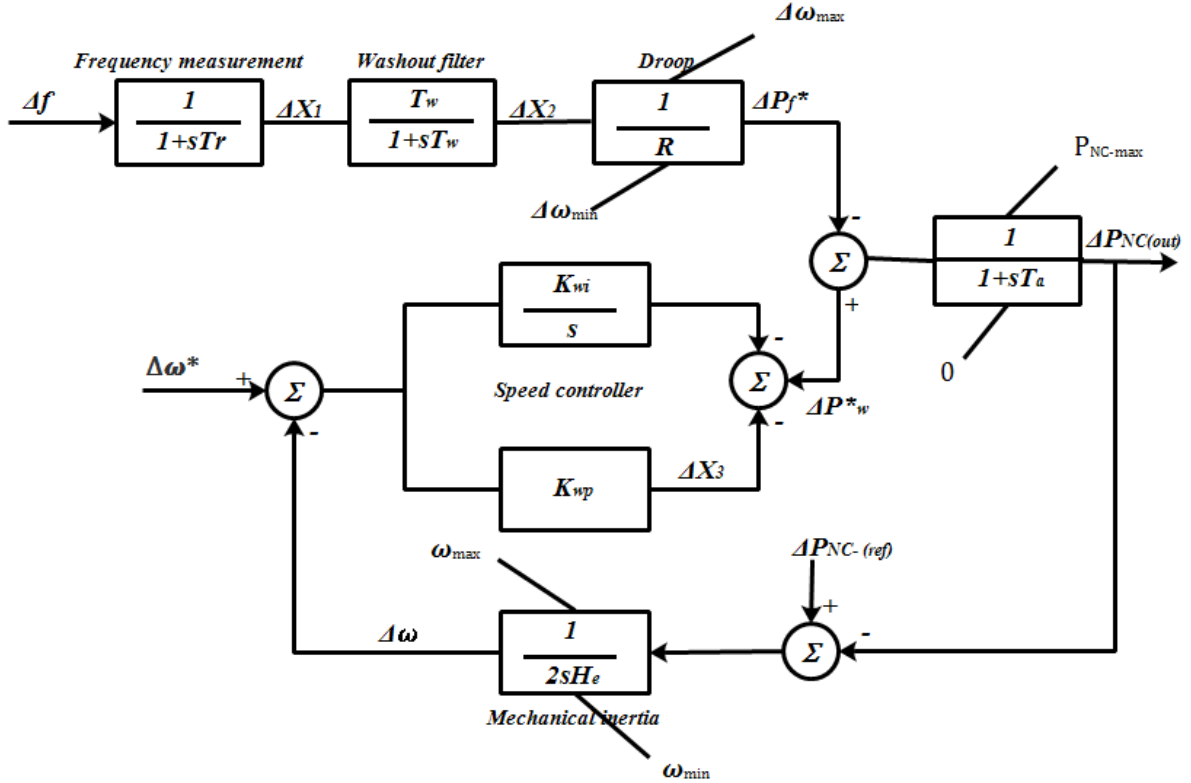


Fig 2.12: DFIG-based wind turbine control based on frequency deviation

In Fig 2.12 participation of DFIG based wind turbine to maintain system inertia can be seen. The only change in this figure as compared to Fig 2.10 is setting another reference power based on the frequency change using washout filter using time constant (T_w) which depend upon response of primary control of conventional unit during transient.

$$J_1 = \int_0^{\infty} (ACE_1)^2 dt \quad (2.50)$$

$$J_2 = \int_0^{\infty} (ACE_2)^2 dt \quad (2.51)$$

2.5.5 Primary frequency control with DFIG-based wind turbine

Dynamic response of thermal (non- reheat) and DFIG wind turbine integrated power system is represented with small perturbation model shown in Fig 2.13 The primary frequency regulation is simulated using this model considering system parameters such as regulation droop (R), the inertia (H), damping factor (D) and time constants (T_h and T_t) of governor and turbine respectively. The behaviour of system depends on the value of system parameters and speed controllers are K_{op} and K_{oi} of DFIG based wind turbine. In the case of several interconnected generators the equivalent regulations drew can be expressed as

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \dots + \frac{1}{R_n} \quad (2.52)$$

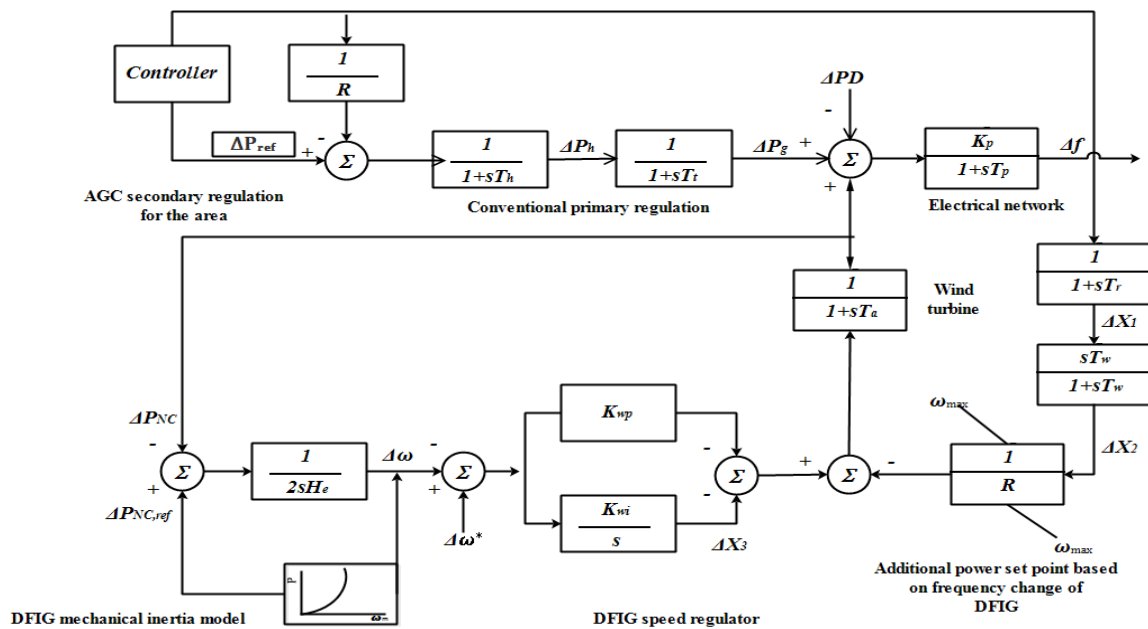


Fig 2.13: Dynamic Model for LFC with DFIG based Wind Turbines

In figure 2.13 (ΔP_h) is position change of incremental governor valve, ($\Delta \omega$) is change in wind turbine speed, (Δf) is change in frequency (ΔX_1) is change in frequency after measuring by transducer (ΔX_2) is change in frequency after filter wash out and (ΔX_3) is incremental frequency change in DFIG integral speed control

2.5.6 Dynamic model of two Area DFIG-based wind integrated system

LFC for multi area wind integrated system are very important and complex as compared to the isolated power system. In single area isolated system the frequency is considered uniformly constant throughout the area. The block diagram of small perturbation transfer

function of two area system for secondary frequency control loop is shown in figure 2.14. Here two thermal integrated with the DFIG wind turbine generator connected through tie lines is considered, where $\Delta\omega_1$ and $\Delta\omega_2$ are changes in wind turbine speed respectively. (ΔP_{NC1}) and (ΔP_{NC2}) are wind power penetration to conventional generators to area 1 and area 2 respectively. (ΔX_{1-1}) is frequency change after measured by transducer; (ΔX_{2-1}) change in frequency after filter wash out and (ΔX_{3-1}) is the incremental change in speed control of DFIG wind turbine of area 1 and area 2 respectively.

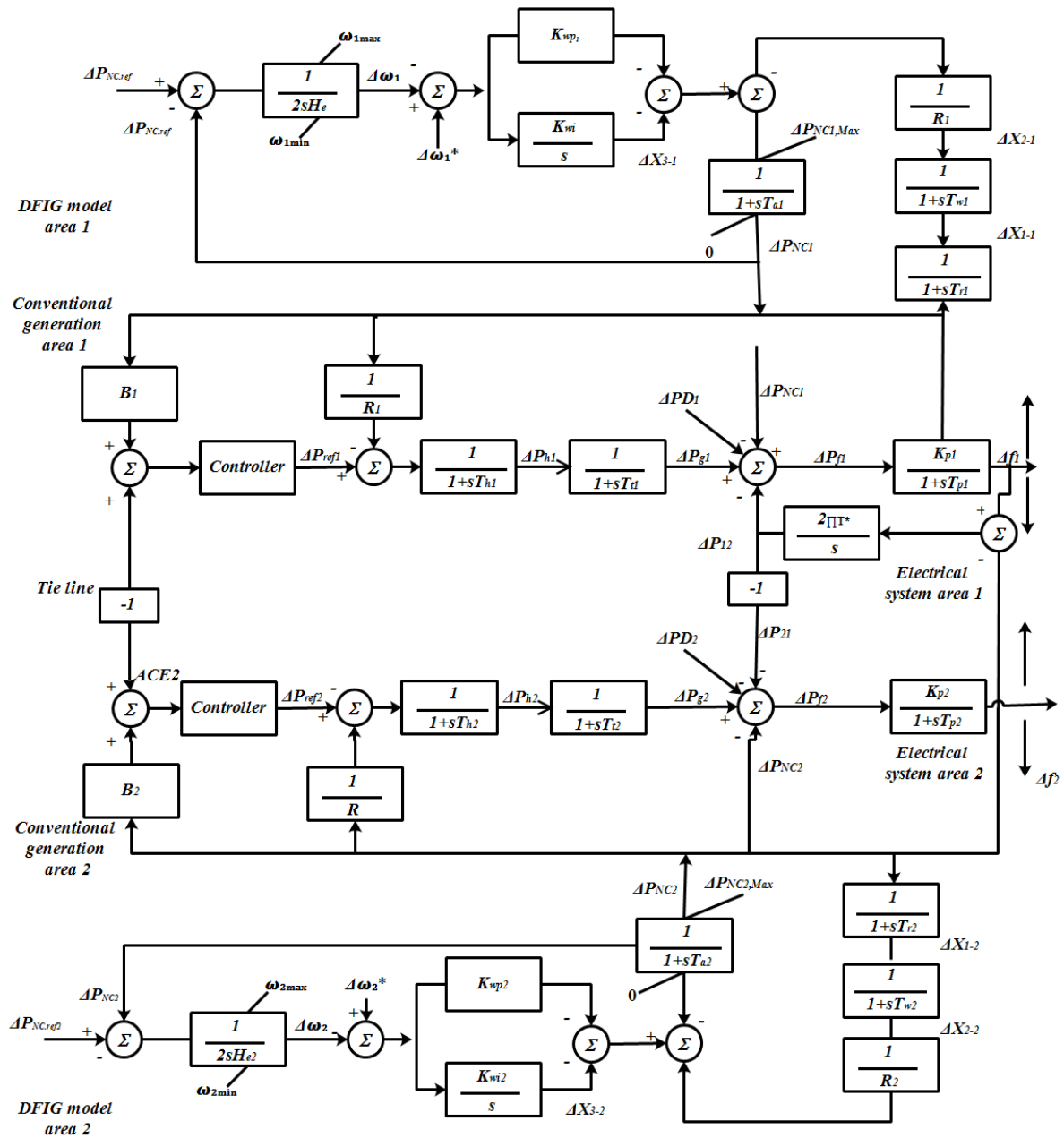


Fig 2.14: Linearized model of wind integrated two area systems with secondary control loop

CHAPTER 3

RESEARCH METHODOLOGY

3.1 PROPORTIONAL-INTEGRAL (PI) CONTROLLER

In most of the industries proportional integral PI controllers are effectively and widely used for decades due to its simplicity. Therefore, these controllers are known as conventional controllers. In general LFC consist two loops primary and secondary speed control in interconnected power system. The initial frequency adjustment is done by primary speed control. Due to which all generators in that area sense that load variation and divide the new demand as per their capacities. The controlling action is limited by the time constants of turbine, governor and power system loads. The secondary loop is responsible for adequate regulation of frequency by settling down frequency error to zero using integration operator of PI controller.

3.1.1 Limitations of conventional PI controller

- Action of controller is slow.
- The control action against inherent nonlinearity is not up to the mark. This nonlinearity in the system is due to dead band of governor; reheat steam turbines, generation rate constraints (GRC) etc.
- Rapid load change in daily load cycle causes a change in set point at all instant which is an inherent property of the power system. Thus the Integrator gain should change rapidly for low peak overshoot and fast transient recovery, which is almost practically impossible.
- Participation of variable speed DFIG wind turbines in primary frequency control interconnected system.

3.1.2 Optimal tuning of PI controller

There are various methods used by authors to find the optimal value of the gains of PI controllers. The Ziegler-Nichols suggested simplest experimental method to find the optimal value of gains K_p and K_i to control optimization problem. In this method integral and derivative gains are set to zero.

ZIEGLER–NICHOLS method for tuning PI controller

The ZIEGLER–NICHOLS tuning method is a heuristic method of tuning PID controller developed by John G Ziegler and Narhanial B. Nichols. It is performed by setting the integral and derivative gains to zero .The K_p gain is then increased from zero until it reaches the ultimate gain K_u at which the output of control loop has stable and consistent oscillation. K_u and oscillation period T_u are used to set the P, I, D depending on type of controller used.

Table 3.1: Various parameters to find PID controller gains.

Types of controller	Proportional gain (K_p)	Integral gain (K_i)	Derivative gain (K_d)
P	$0.5K_u$	-	-
PI	$0.45K_u$	$T_{u/1.2}$	-
PD	$0.8K_u$	-	$T_{u/8}$
Classical PID	$0.6K_u$	$T_{u/2}$	$T_{u/8}$
Pessen Integral Rule	$0.7K_u$	$T_{u/2.5}$	$3T_{u/20}$
Some overshoot	$0.33K_u$	$T_{u/2}$	$T_{u/3}$
No overshoot	$0.2K_u$	$T_{u/2}$	$T_{u/3}$

The ultimate gain (K_u) can expressed as $1/M$. Where, M is amplitude ratio. These three parameters are used to establish the correction $u(t)$ from the error $e(t)$ via equation(3.1).

$$u(t) = k_p(e(t) + \frac{1}{T_i} \int_0^t e(\tau) dT + T_d \frac{de(t)}{dt}) \quad (3.1)$$

$$u(t) = k_p(e(t) + \frac{1}{T_i} \int_0^t e(\tau) dT + T_d \frac{de(t)}{dt}) \quad (3.2)$$

Which has following transfer function relationship between error and controller output

$$u(s) = k_p(1 + \frac{1}{T_i s} + T_d s)e(s) = k_p(\frac{T_d T_i s^2 + T_i s + 1}{T_i s})e(s) \quad (3.3)$$

Evaluation

The Zieler–Nicholas, turning creates “quarter wave decay”. This is an acceptable result for some purpose not optimal for all applications. This tuning rule is meant to give PID loops best disturbance rejection .It yields an aggression gain and overshoot. Some applications wish to instead minimize or eliminate overshoot and for these this method is an appropriate.

3.2 ARTIFICIAL NEURAL NETWORK (ANN) CONTROLLERS

The artificial neural network is an intelligent technique used in various optimization problems. ANN controllers are based on the structure of the human brain. The working of these controllers is also very similar to the brain as they learn from previous knowledge. The controller saves previous information which is used to construct an enormous parallel network and trained them to solve definite problems. The basic constituent of the human brain is a special kind of cell called neurons, which stores information and reflects previous experience while performing similar task. Similarly, ANN controllers are made up of neurons which are extremely complex non-linear and parallel processing systems. These controllers are divided into three layer input layer, a hidden layer, and the output layer. Input layer carries signals to be hidden layers where computation is done and finally the output signals come out through output layer. The ANN controllers are trained using Back Propagation algorithm [22].

3.2.1 The basic features of neural networks are [23]:

- Fast computation due parallel functioning.
- Heavy error acceptance
- Simple computation
- Goal-seeking
- Learning nature from the past

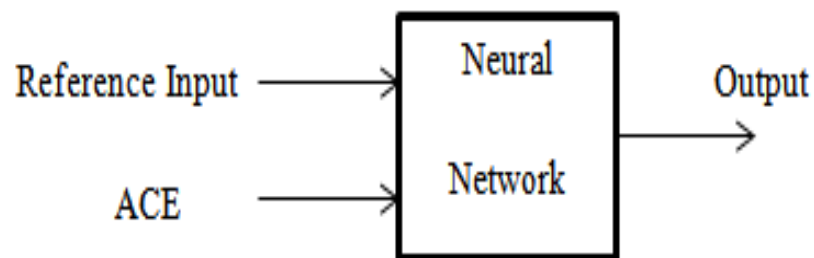


Fig 3.1: Architecture of Artificial Neural Network (ANN)

3.2.2 Back Propagation algorithm

The BP algorithm is extremely renowned as the widely used neural paradigm [28]. Terence Sejnowski was first to determine the BP algorithm. The BP algorithm is discussed below

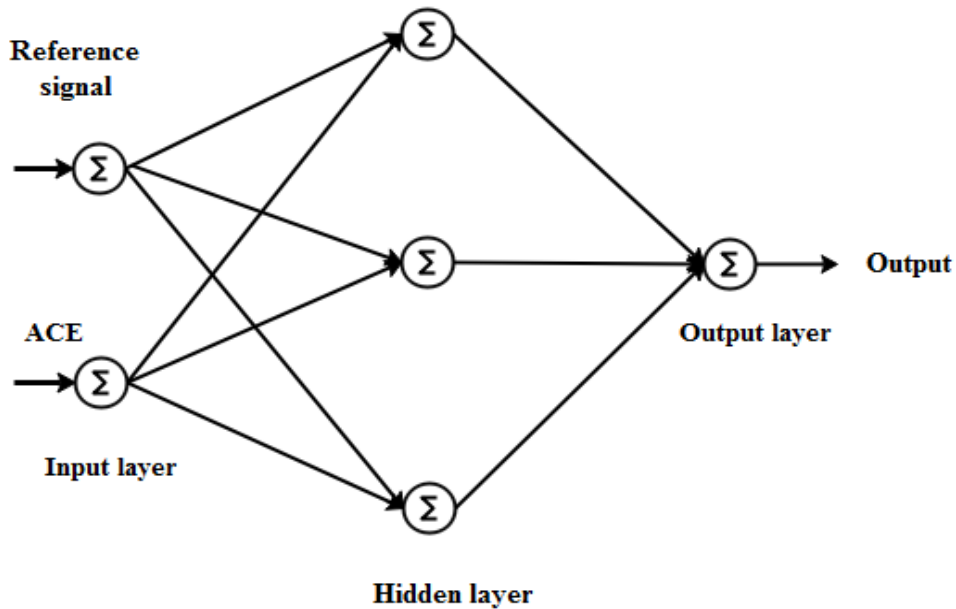


Fig 3.2: Multi-layer Feed Forward Network

Algorithm

Step 1: Initialization

All threshold points the weights and of the network to random numbers homogeneously distributed inside a small range

$$-\frac{0.05}{F_i}, +\frac{0.05}{F_i} \quad (3.4)$$

Where, F_i is the total inputs to neurons i in the network

Step 2: Activation

Calculate the actual outputs of the neurons in the hidden layer:

$$y_j(p) = \text{sigmoid} \left[\sum_{i=1}^n x_i(p) \cdot w_{ij}(p) - \theta_i \right] \quad (3.5)$$

Where n is the number of inputs of neuron, j is the hidden layer and Activation function is *sigmoid*

Calculate the real outputs of the neurons in the output layer:

$$y_k(p) = \text{sigmoid} \left[\sum_{i=1}^n x_{jk}(p) \cdot w_{ik}(p) - \theta_k \right] \quad (3.6)$$

Step 3: Weight training

The error gradient has been calculated for the neurons in the output layer:

$$\delta_k(p) = y_k(p)[1 - y_k(p)] \cdot e_k(k) \quad (3.7)$$

Calculate the modified weight

$$e_k(k) = Y_{d,k}(p) - y_k(p) \quad (3.8)$$

The weights are updated at output neuron

$$\Delta w_{jk}(p) = \alpha \cdot y_j(p) \delta_k(p) \quad (3.9)$$

$$\Delta w_{jk}(p+1) = w_{jk}(p) + \Delta w_{jk}(p) \quad (3.10)$$

The error gradient has been calculated for the neurons in the hidden layer

$$\delta_j(p) = y_j(p)[1 - y_j(p)] \cdot \sum_{n=1}^l \delta_k(p) w_{jk}(p) \quad (3.11)$$

Now determine the corrected: weight

$$\Delta w_{jk}(p) = \alpha \cdot x_i(p) \delta_j(p) \quad (3.12)$$

Weight has been updated at the hidden neuron:

$$\Delta w_{jk}(p+1) = w_{jk}(p) + \Delta w_{jk}(p) \quad (3.13)$$

Step 4: Iteration

Iteration number p has been increased by one, and the whole process from step 2 has been repeated till we get anticipated result.

Recently, the back propagation algorithm has been widely used for various optimization problems in different fields. It gives better outcomes as compared to other conventional techniques. Therefore, this technique was also implemented for designing controllers for various problems.

3.2.3 NARMA L_2 controller

The NARMA L_2 controller is a robust controller in artificial neural network. It is known for non-linear auto-regressive model adaptive controller. It reduces the complex computation of non-linear system to three architectures. This controller can be designed by recombining the plant model, and it can be trained offline in batch form. The working principle of this controller is to nonlinear system dynamic transformation into linear by terminating nonlinearities. The controller has two input ports reference, plant output signal and single output control signal port. The reference signal is enforcedly tracked by plant output. The various steps to run these controllers are as follows

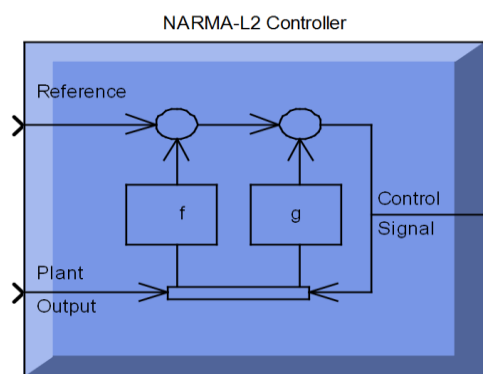


Fig 3.3: Block diagram of NARMA-L2 Controller

System identification: The first step while using feedback linearization or NARMA L_2 control is to identify the system model.

Controller design: The control system is represented as approximated discrete time nonlinear system and expressed as equation (3.14)

$$y(k + d) = N[y(k), y(k - 1), \dots, y(k - n + 1), u(k), u(k - 1), \dots, u(k - n + 1)] \quad (3.14)$$

In load frequency control problem ACE from plant output is fed to controller input port and a reference signal is produced to train the controller such that to force plant output to mimic the reference value. The control action continues to work until controller input and reference signal becomes same. After the comparison between plant output and reference signals the error signal is generated by a controller which is used to feed as a control signal to the governor inlet valve. The ACE, load change and frequency disturbance as input to the controller is obtained from PID controlled plant. The control signal which is output of the neural network fed to the governors of the area.

Step 1 Plant identification

Here, the controller uses perceptron of four layers and one input, 15 neurons in the hidden layer, and one output. Train-lm function is used as activation function for neural network. The 1000 number of training samples has been reserved to train 10 numbers of epochs. The proposed network uses learning performance.

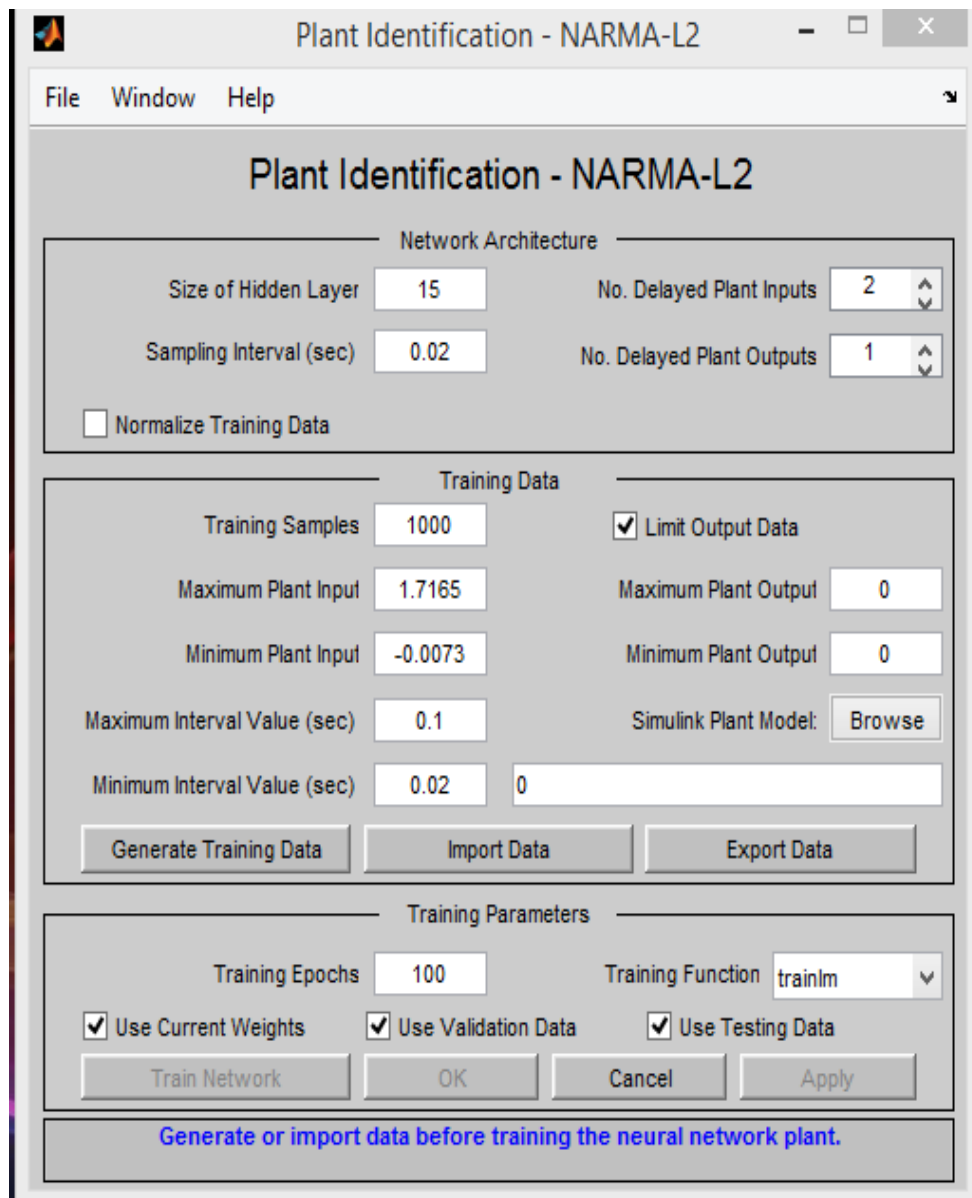


Fig 3.4: Plant identification of NARMA L2 controller

Step 2 Data import

Then data is imported from array & structures with sampling interval (0.02 sec) with input array (ace1) and output array (delf1) with 419 generated training samples as shown in Fig 3.5 and 3.6

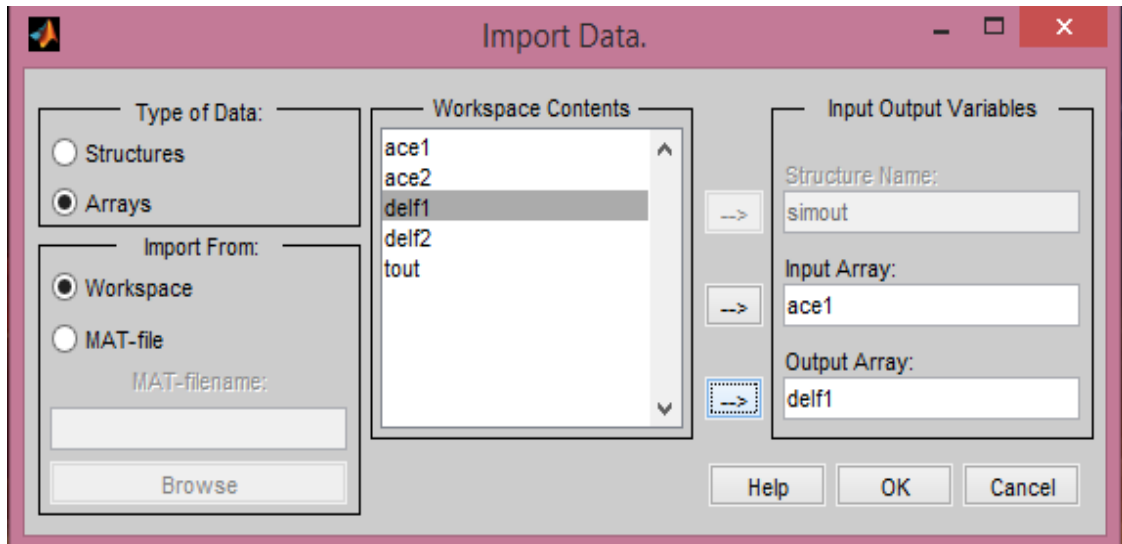


Fig 3.5: Data import process with structures and arrays

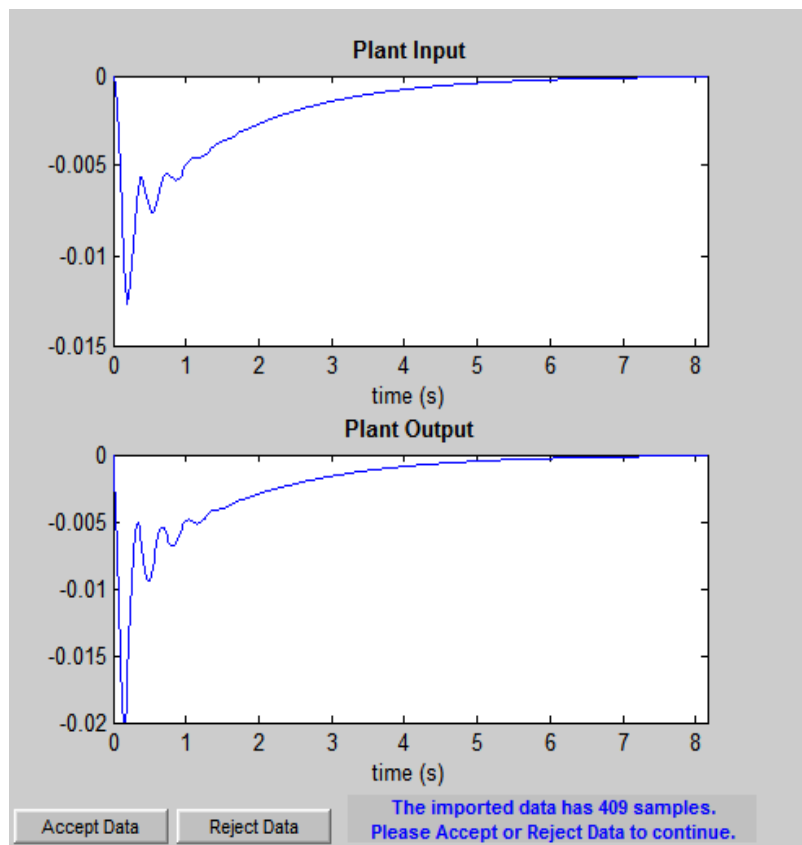


Fig 3.6: Plant Input-Output Data Controller

3.2.4 Training NARMA L₂ controller for LFC problems

NARMA L₂ works on the past learning methodology of the plant model output. The input data to the NARMA L₂ is the ACE signal coming from feedback of plant model. The other input signal is the reference value which we need as the desired output from the plant. The training data for the load frequency control problem is generated through optimized PI controlled model of two area system. The input as well as output signals to PI controller is imported in the network for training purpose. The small part of training data are used as validation data and testing data. The performance of the ANN controller is shown by performance, auto regression of the controller for training, testing and validation data as shown in Fig. [3.7-3.12] [20].

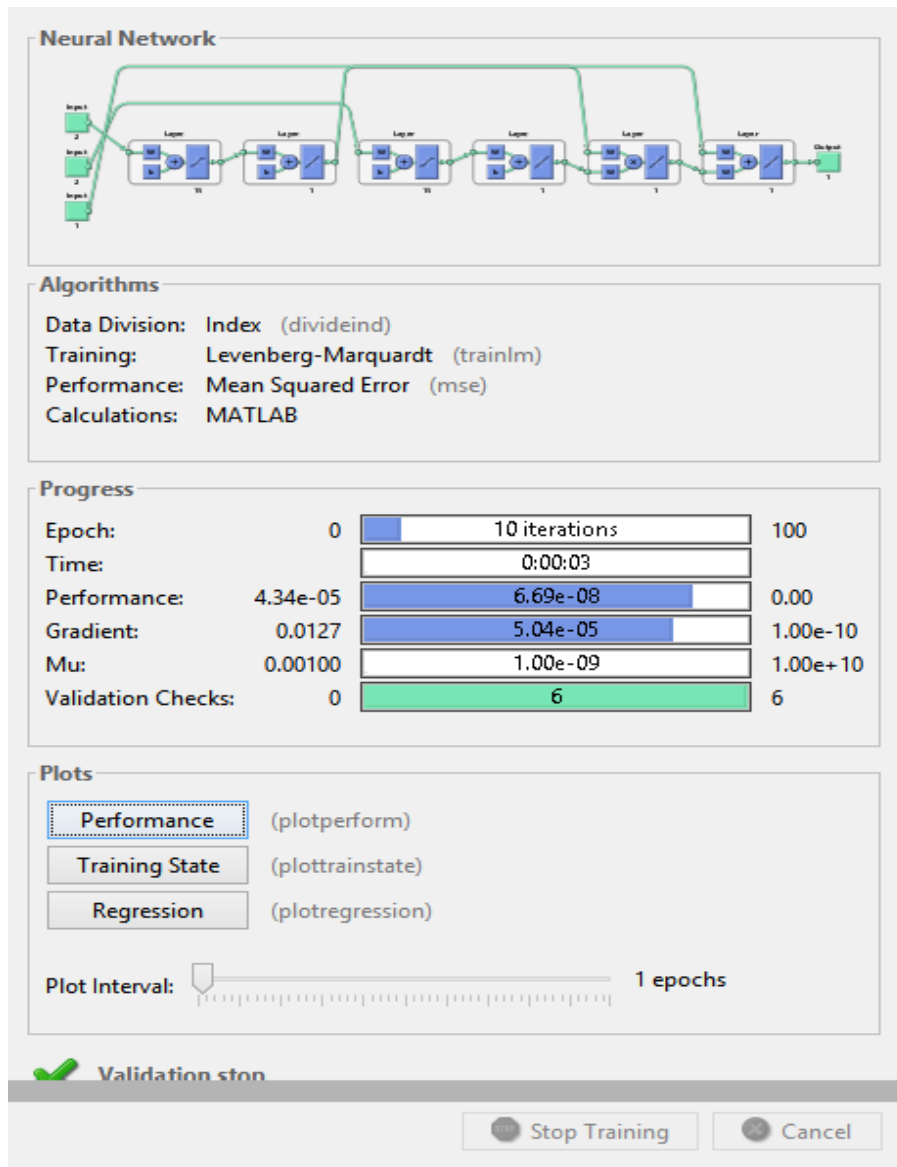


Fig 3.7: Neural Network Controller Training Tool

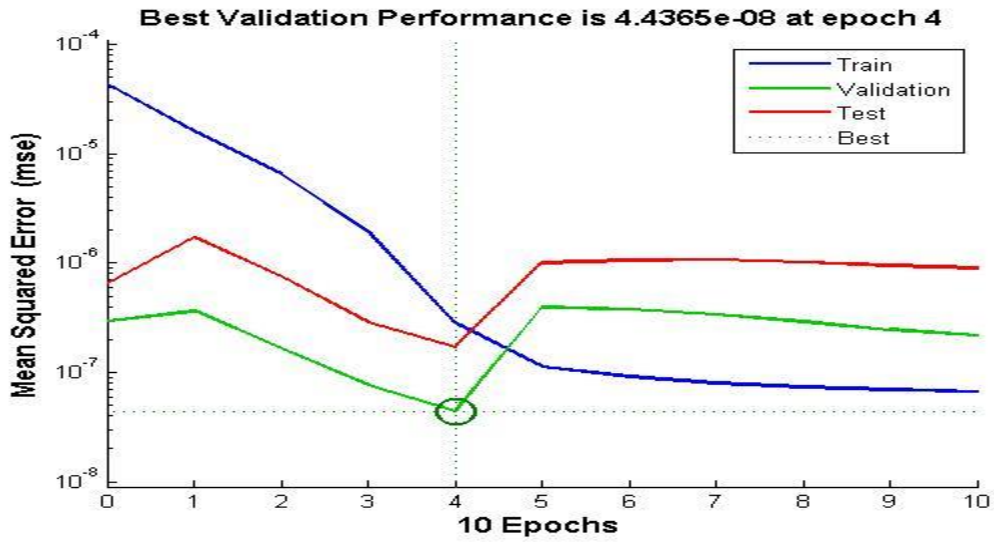


Fig 3.8: Controller Performance

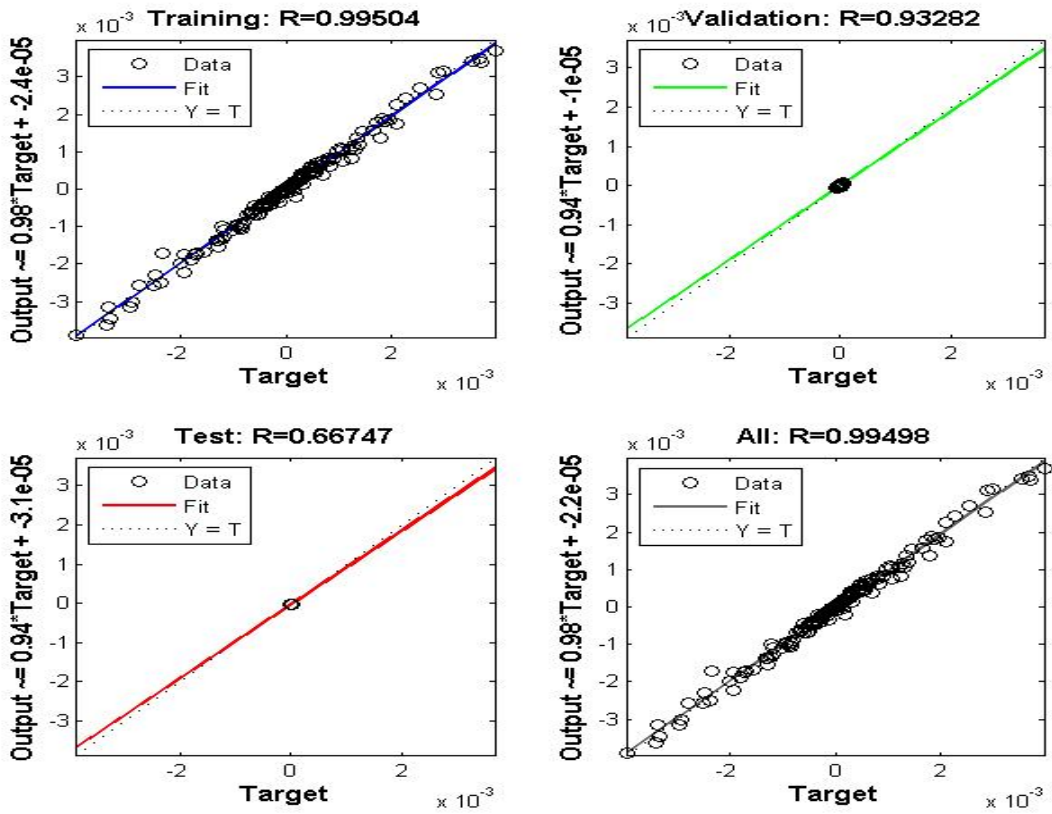


Fig 3.9: Controller Regression

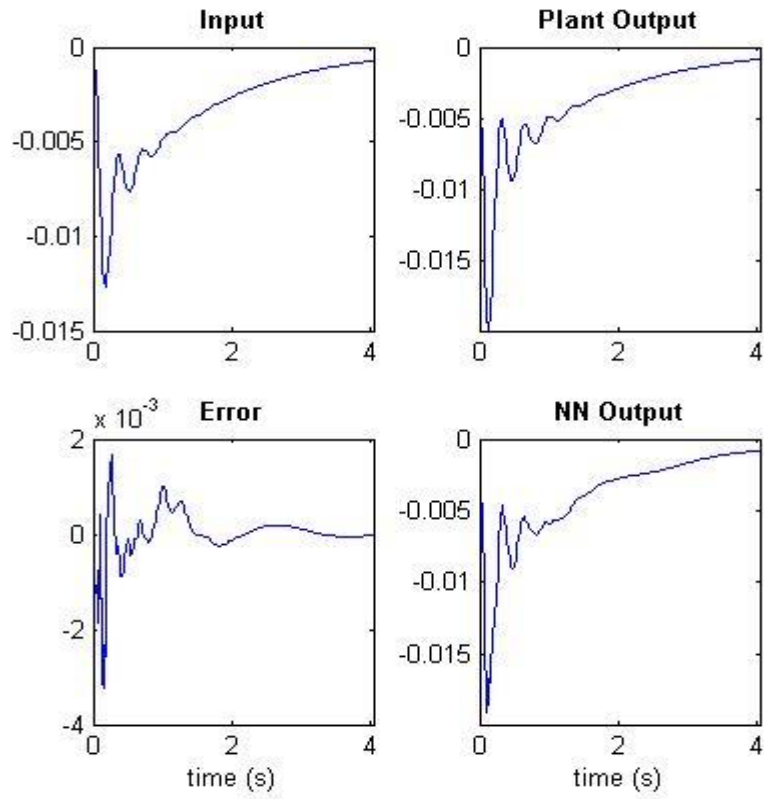


Fig 3.10: Training Data

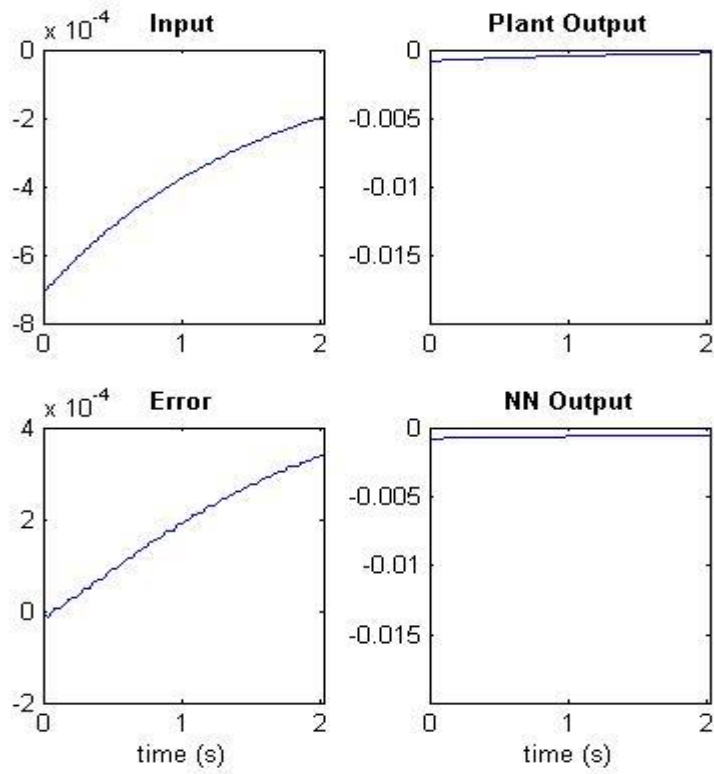


Fig 3.11: Validation Data

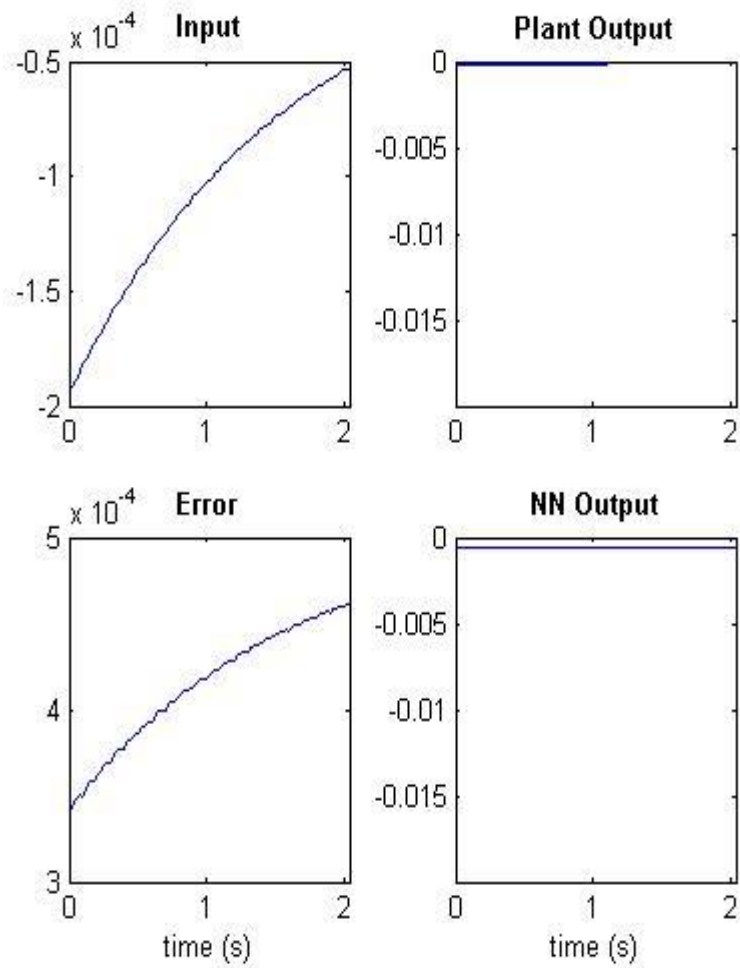


Fig 3.12: Testing Data

Thus, finally the plant model runs to give the output for the NARMA L2 model. The output will be stored in the Matlab workspace

CHAPTER 4

SIMULATION AND RESULTS

4.1 LOAD FREQUENCY CONTROL USING PI CONTROLLER

The basic control method widely used in current power generating industries is proportional integral controllers over more than a decade. Here PI controller is used as a conventional controller to limit the change in frequency of different load change in the two areas interconnected systems.

4.1.1 Simulink model of two area system without wind turbines

Mainly thermal (steam) power generators are known as conventional plants as large parts of the power produced through it. Although these plants are having a high power generating cost apart from this fact, it is a more reliable source to fulfil large block of loads. The Matlab / Simulink model to the PI controller for two areas system is shown in fig. 4.1

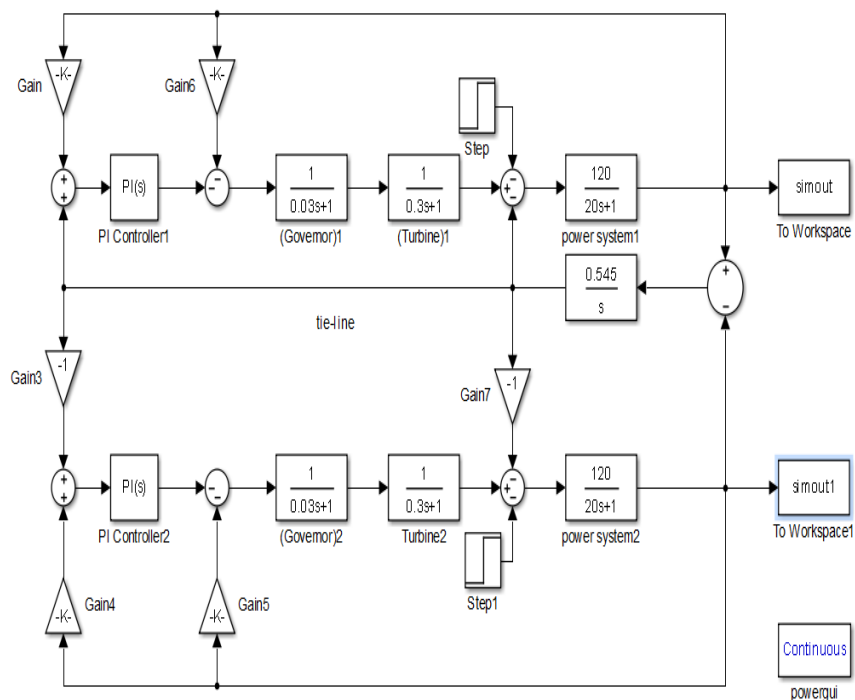


Fig 4.1: Simulink model of two area load frequency control with PI controller

All the optimized gains of PI controllers are set in the controllers. The optimized values of the gains are tabulated in table 4.1

Table 4.1: The values of gains of optimized PI controller in system without wind

S.No.	ΔP_L	k_{p1}	k_{i1}	k_{p2}	k_{i2}
1	0.01	0.6	0.3	0.5	0.2
2	0.05	1.72	0.75	0.8	0.6

4.1.2 Simulink model of two area systems with wind penetration

As the conventional or non-renewable sources are available in limited volume and also costlier than renewable sources. There to fulfil the proper demand of power, at least cost the integration of renewable sources is being practiced. Although the conventional plants are used as base plants the renewable power generators plays an important role against variable power demand.

The wind turbines are more economical as well as reliable sources of electricity. The integration of wind turbine generators with conventional generators is done by the parallel connection of both the generators working as a coherent group in the single control area. The wind turbines may also be situated near to the load to feed them. The both generators may be controlled independently, or there may be coordinated control for achieving better stability in the system.

The Matlab/Simulink model of wind integrated two area power system is shown in fig 4.2

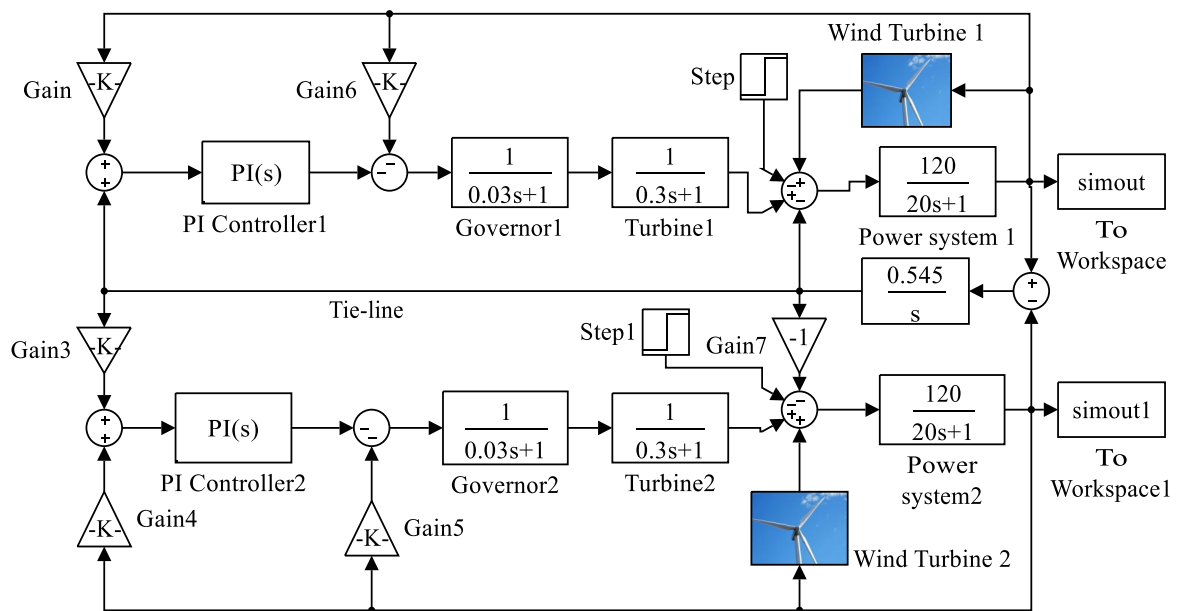


Fig 4.2: Wind integrated two area load frequency control model using PI controller

All the optimized gains of PI controllers are set in the controllers. The optimized values of the gains are tabulated in table 4.2

Table 4.2: The optimal value of gains of PI controllers in system with wind

S. No.	ΔP_L	k_{p1}	k_{i1}	k_{p2}	k_{i2}	k_{pw1}	K_{iw1}	k_{pw1}	k_{pw1}
1	0.01	0.6	0.3	0.5	0.2	0.3	0.08	0.3	0.08
2	0.05	1.7	0.75	0.8	0.6	0.5	1.2	1.2	0.5

4.2 LOAD FREQUENCY CONTROL USING NARMA L2 CONTROLLER

4.2.1 Simulink model of two area system without wind penetration

This model describes the effect of the NARMA L2 controller on the thermal generators of both the areas. The parameters of the controllers are set inside it to train them for the two area model. The characteristics of thermal power plant are almost linear. Therefore, The NARMA L2 controller is not much effective than PI in this case.

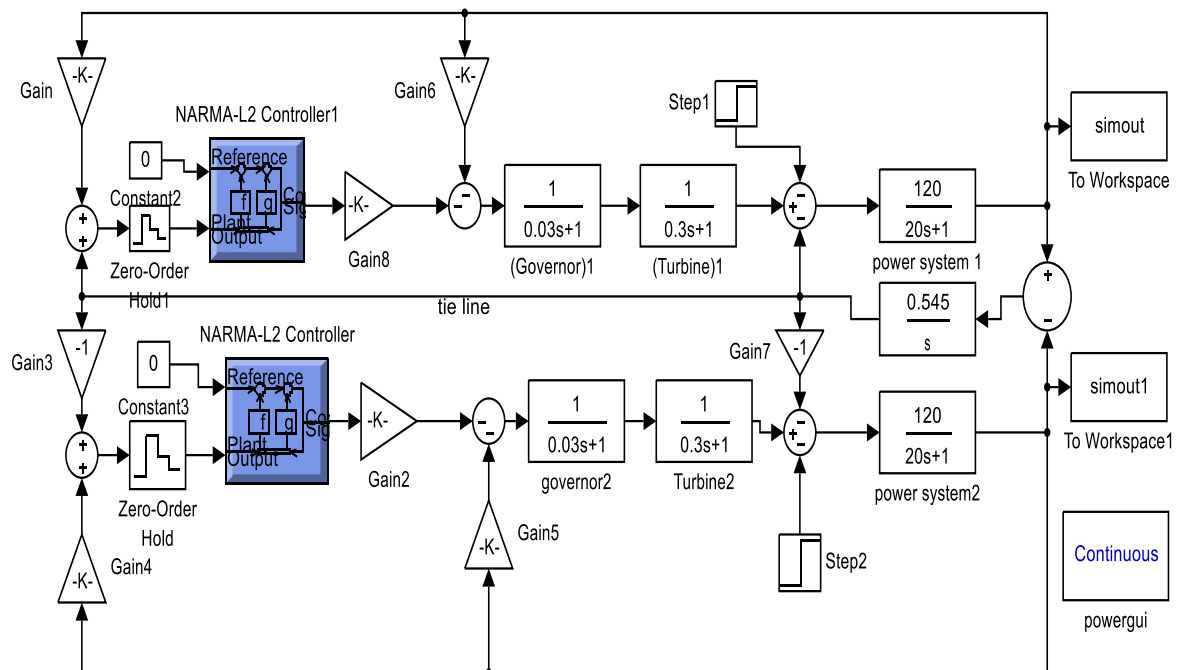


Fig 4.3: Simulink model of two area load frequency control with NARMA controller

4.2.2 Simulink model of two area system with wind penetration

The model includes wind turbine in each area which participate in frequency and real power control. The wind turbines inject non-linearity in the system. Therefore the role of NARMA L2 controller becomes highly decisive to respond against non-linearity in power generation control. The parameters for the NARMA L2 controllers are set inside it to train them for each load disturbance.

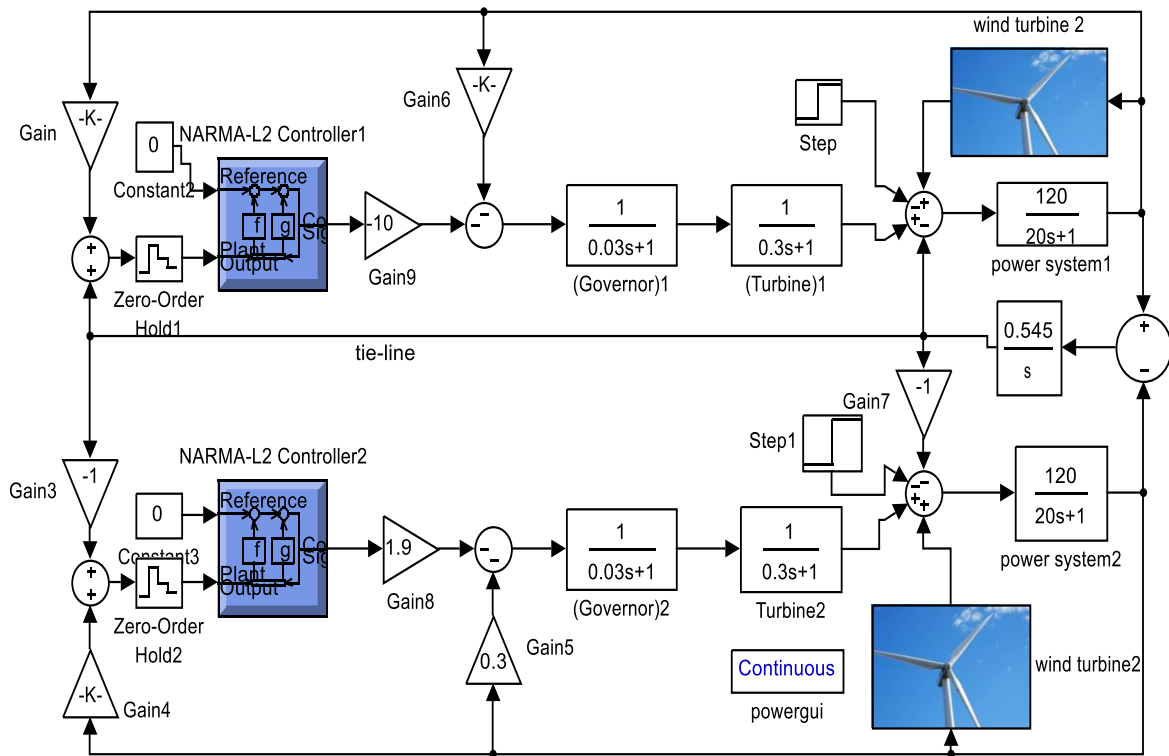


Fig 4.4: LFC of wind integrated two area power system using a NARMA-L2 controller

4.3 RESULTS

4.3.1 Comparative frequency responses of the two area power system using PI and NARMA L2 controllers without wind turbines

The mathematical comparative study of the frequency response of both the controller is complex. A graphical plot makes this study easier through visualization and taking out the maximum and minimum values from graphs. The study has been done for two different load changing conditions 0.01 p.u. and 0.05 p.u. The graphs of both controllers are plotted in same plot to easily compare the controller performance.

Case 1 Dynamic responses with 1% load change in area1

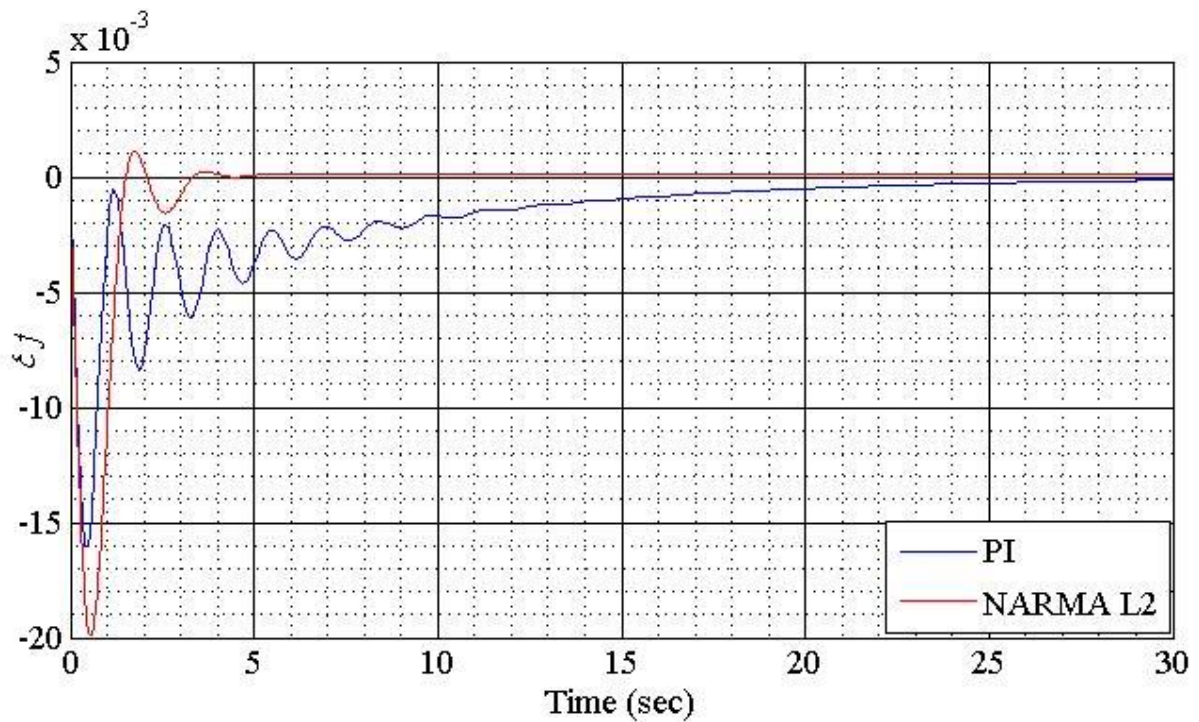


Fig.4.5: Frequency response of area 1 with PI and NARMA L_2 controllers with 1% load change in area 1

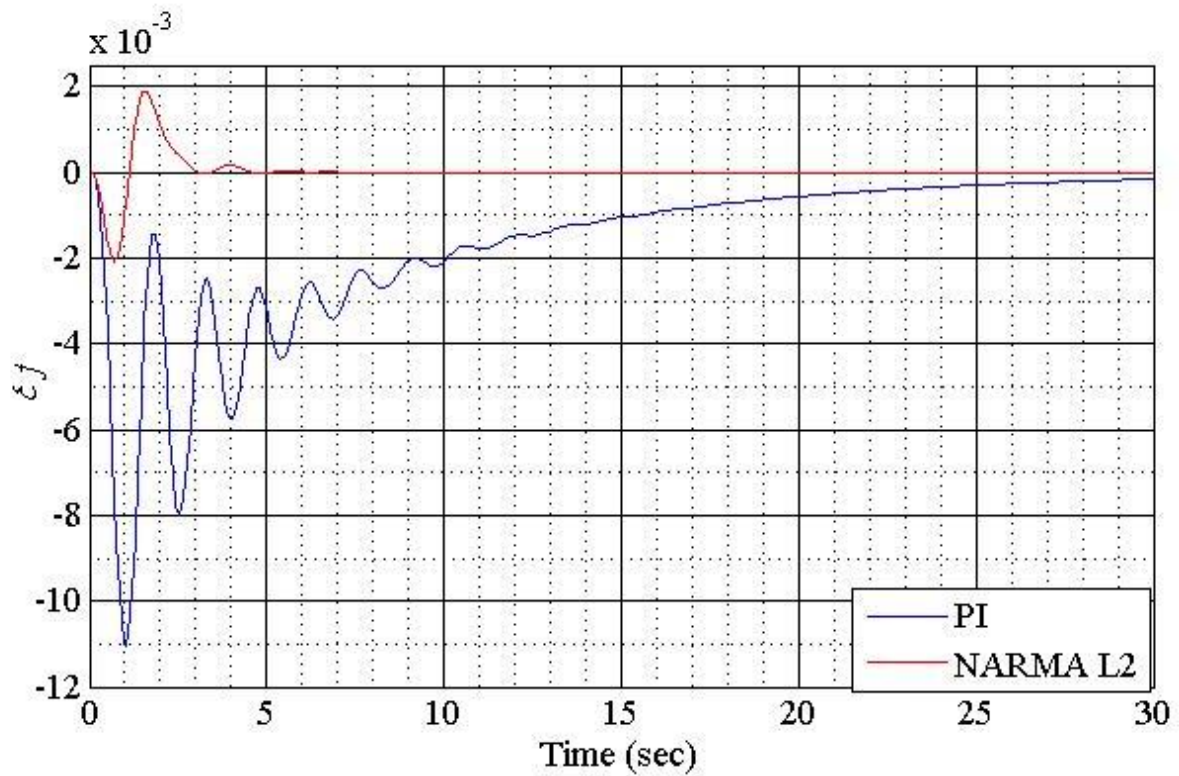


Fig 4.6: Frequency response of area 2 with PI and NARMA L_2 controllers with 1% load change in area1

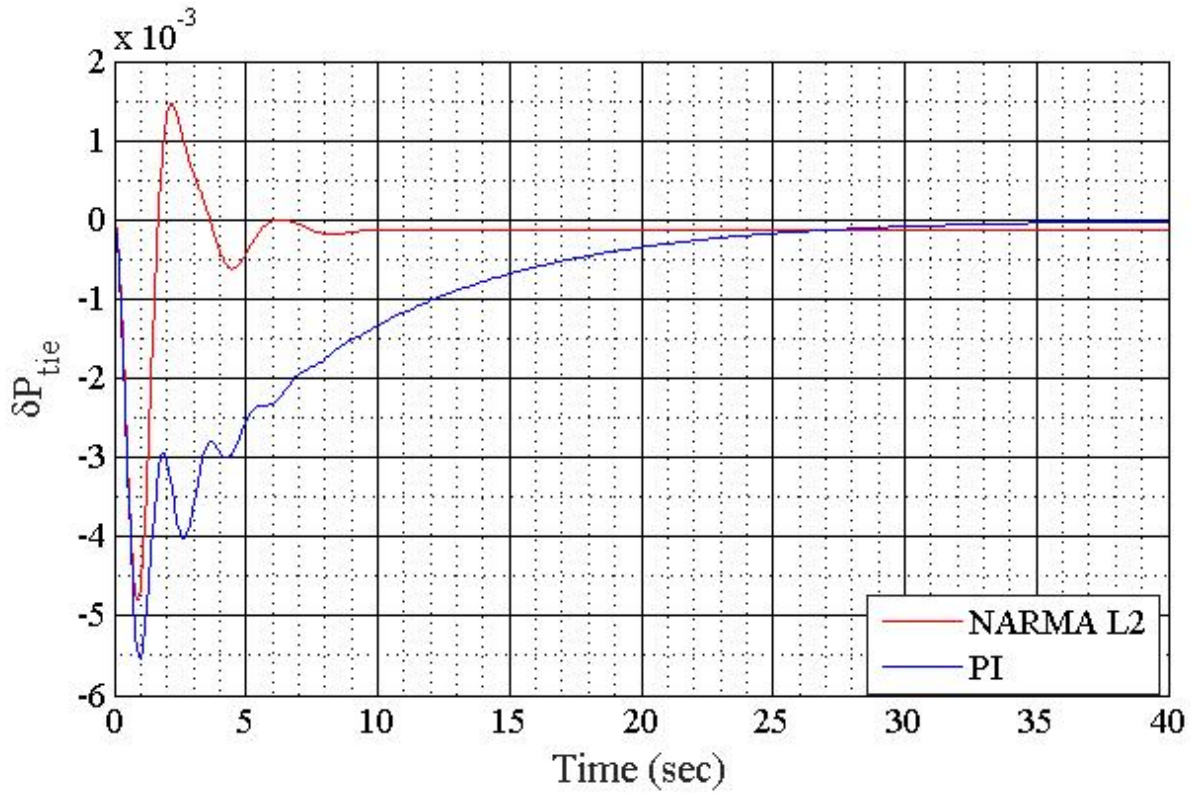


Fig 4.7: Change in tie- line power from area 1 to 2 with 1% load change in area1

Case 2 Dynamic response with 5% load change in area 1

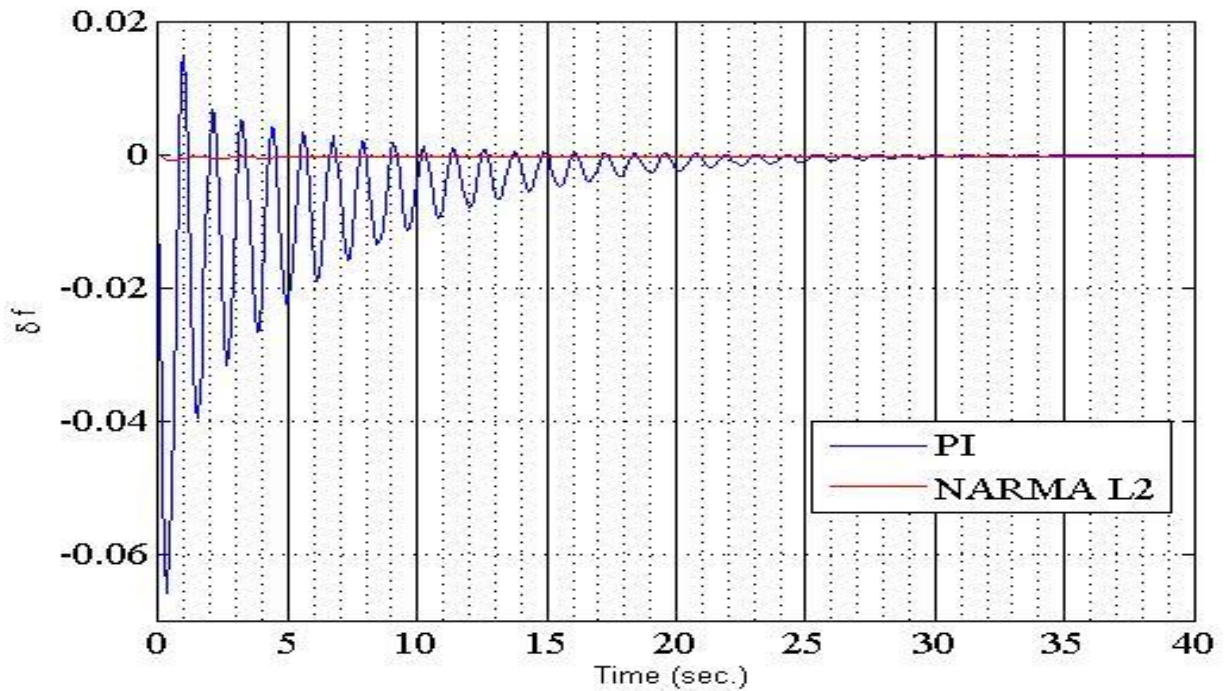


Fig 4.8: Frequency response of area 1 with PI and NARMA L_2 controllers with 5% load change in area 1

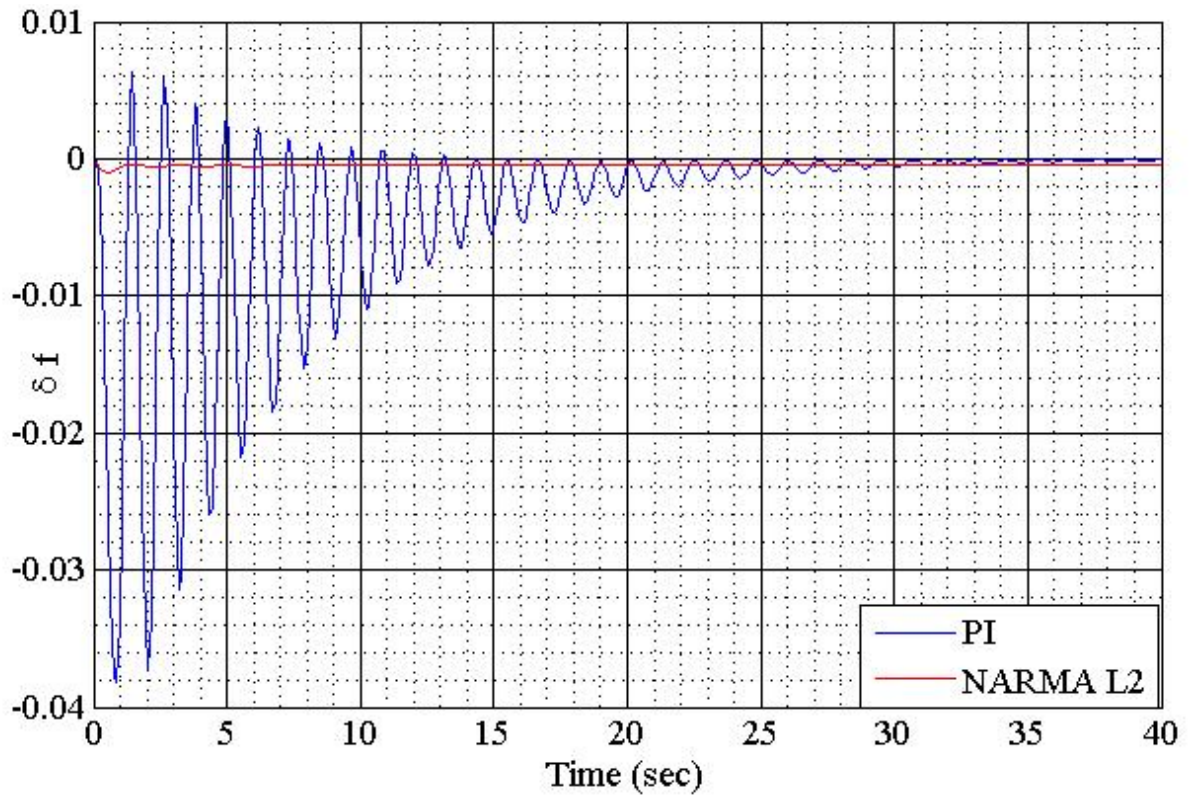


Fig 4.9: Frequency response of area 2 with PI and NARMA L₂ controllers with 5% load change in area 1

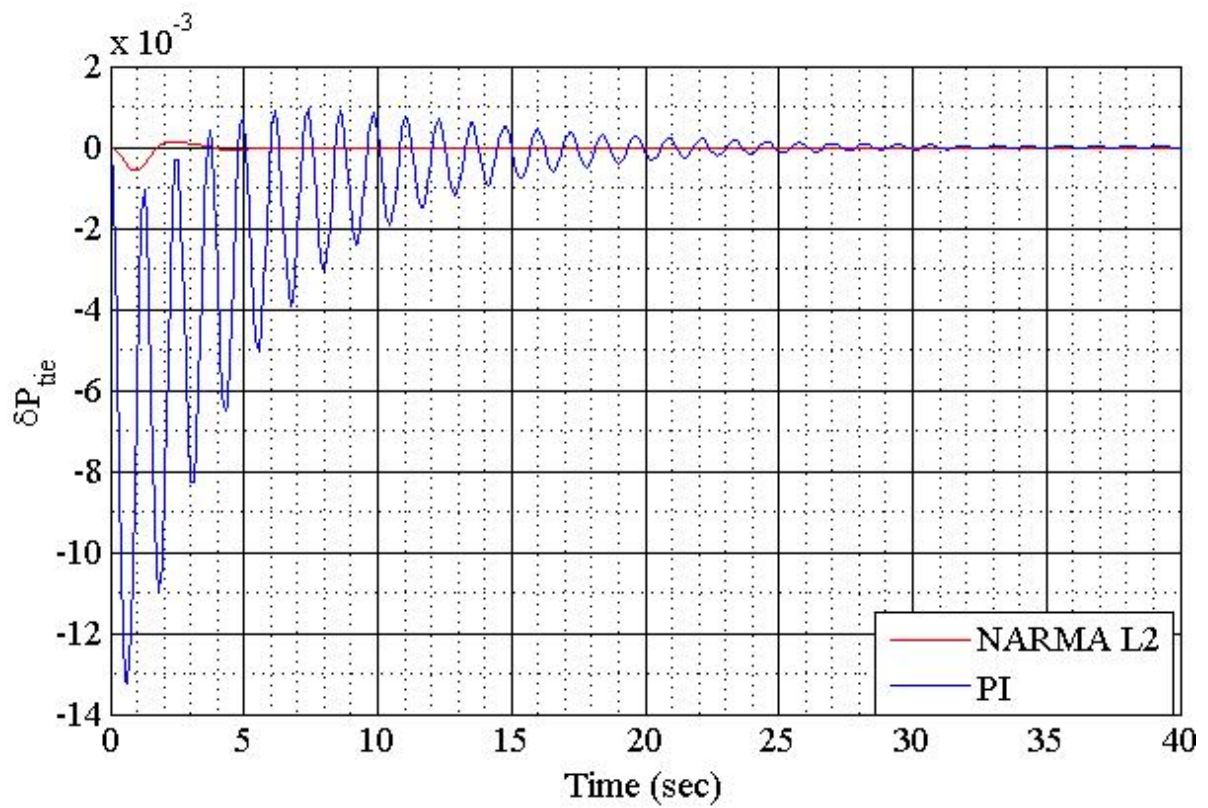


Fig4.10: Tie-line power deviation from area 1 to area 2 with 5% load change in area 1

Table 4.3: Performance comparison of PI and NARMA L2 controllers without WTs

Load Change	PI Controller						NARMA L2 Controller					
	Area 1		Area 2		Tie-lines		Area 1		Area 2		Tie-lines	
	M_p	t_s	M_p	t_s	M_p	t_s	M_p	t_s	M_p	t_s	M_p	t_s
1%	0.016	17	0.011	20	0.0055	20	0.020	4	0.002	3	0.004	5
5%	0.065	21	0.038	24	0.013	23	0.001	5	0.005	4	0.006	7

4.3.2 Comparative frequency responses of the power systems using PI and NARMA L2 controllers with wind penetration

Similarly for DFIG wind turbine integrated system the frequency response by both the controller has been plotted in the same graph for each area for different loading condition. These plots help to show graphically the performance of both the controller in the presence of wind turbine.

Case1 Dynamic response with 1% (0.01 p.u.) load change in area 1

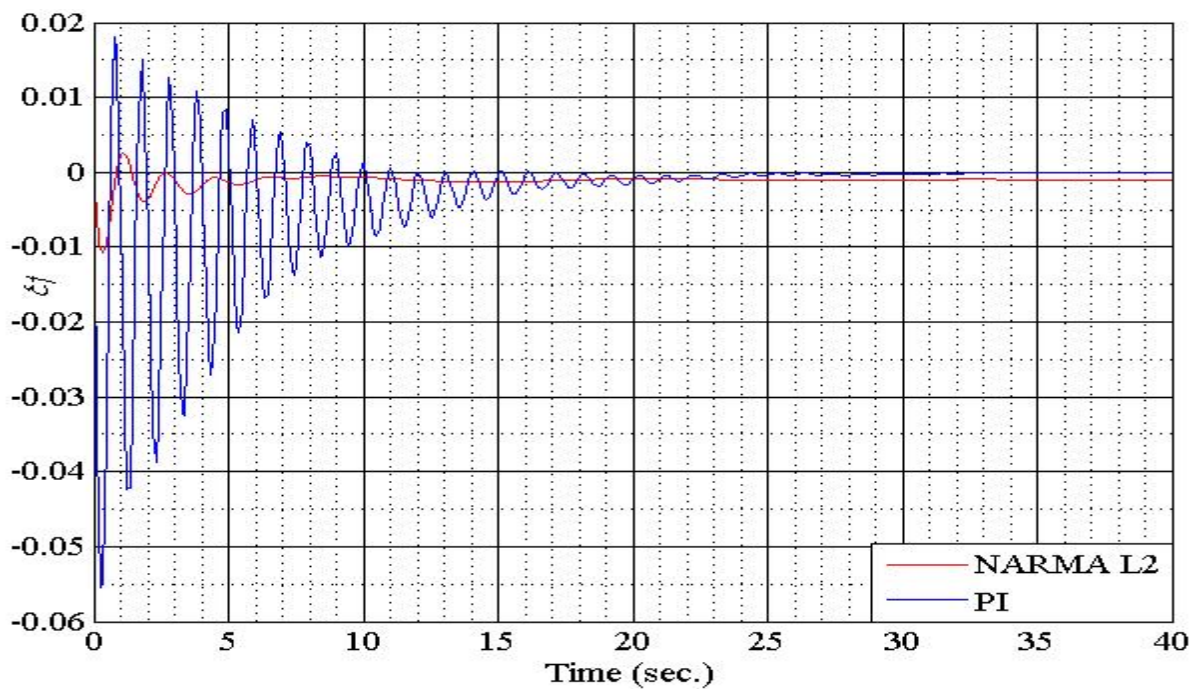


Fig 4.11: Frequency response of area 1 with PI and NARMA L2 controllers due to 1% load change in area 1

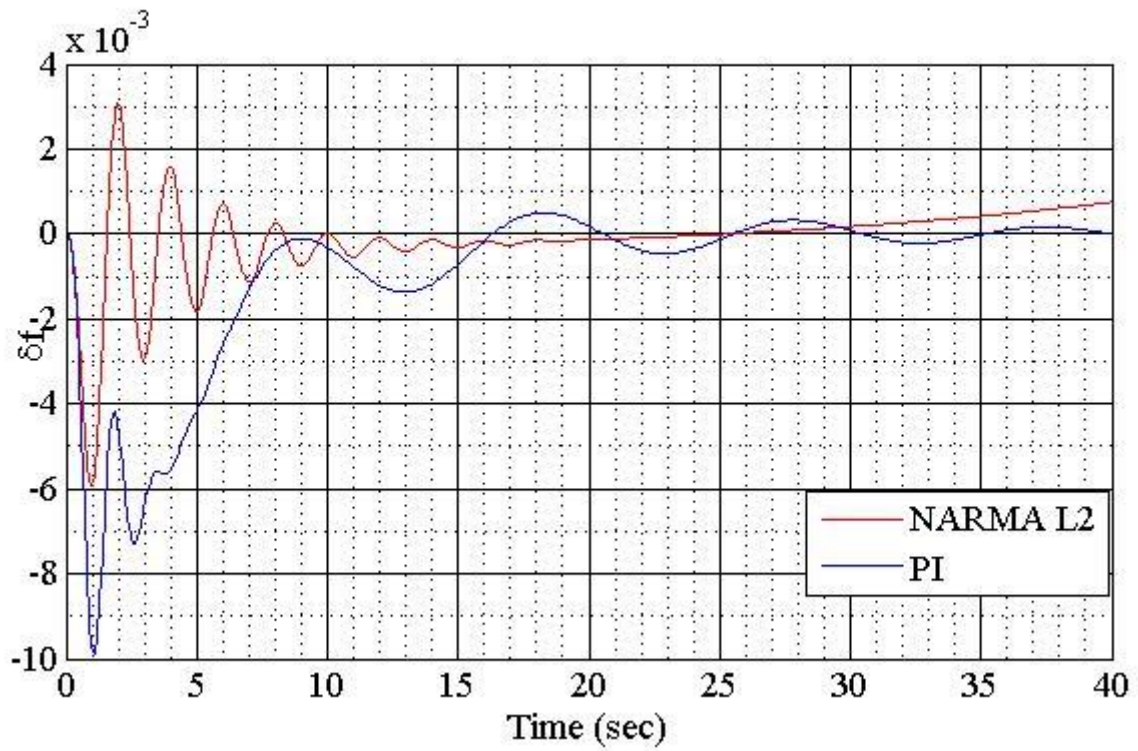


Fig 4.12: Frequency response of area 2 with PI and NARMA L2 controllers with 1% load change in area 1

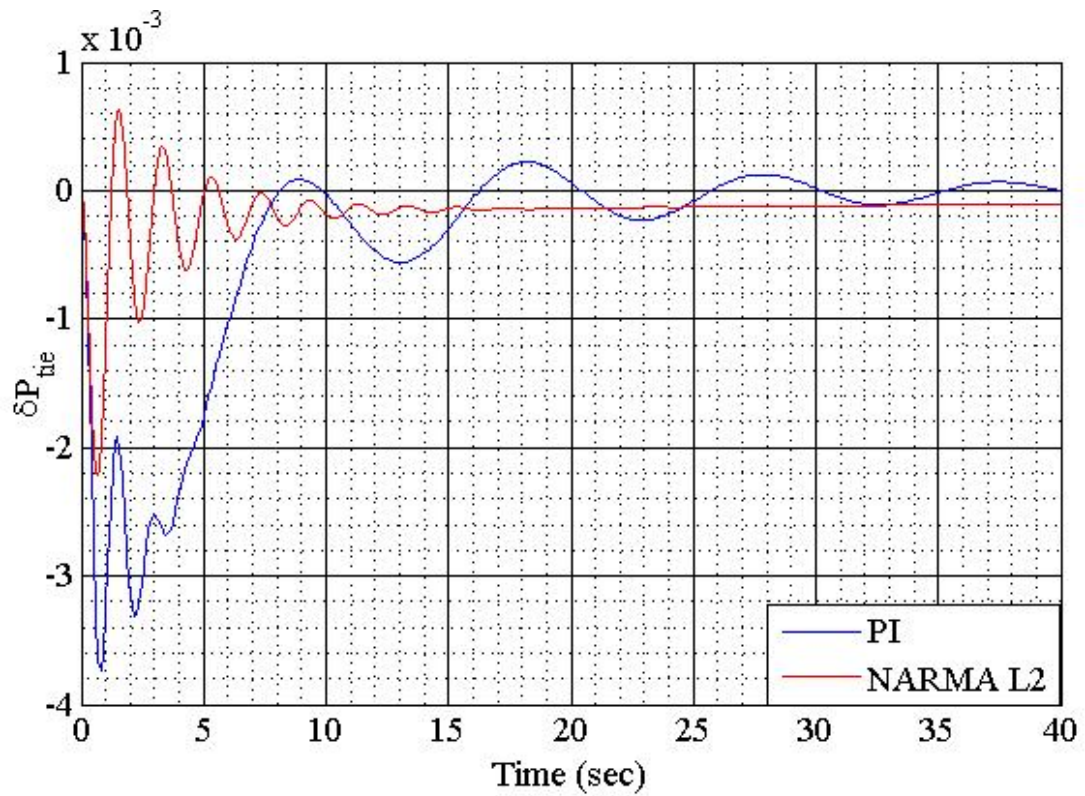


Fig4.13: Tie-line power deviation from area 1 to area 2 with 1% load change in area 1

Case 2 with 5% (0.05 p.u.) load change in area 1

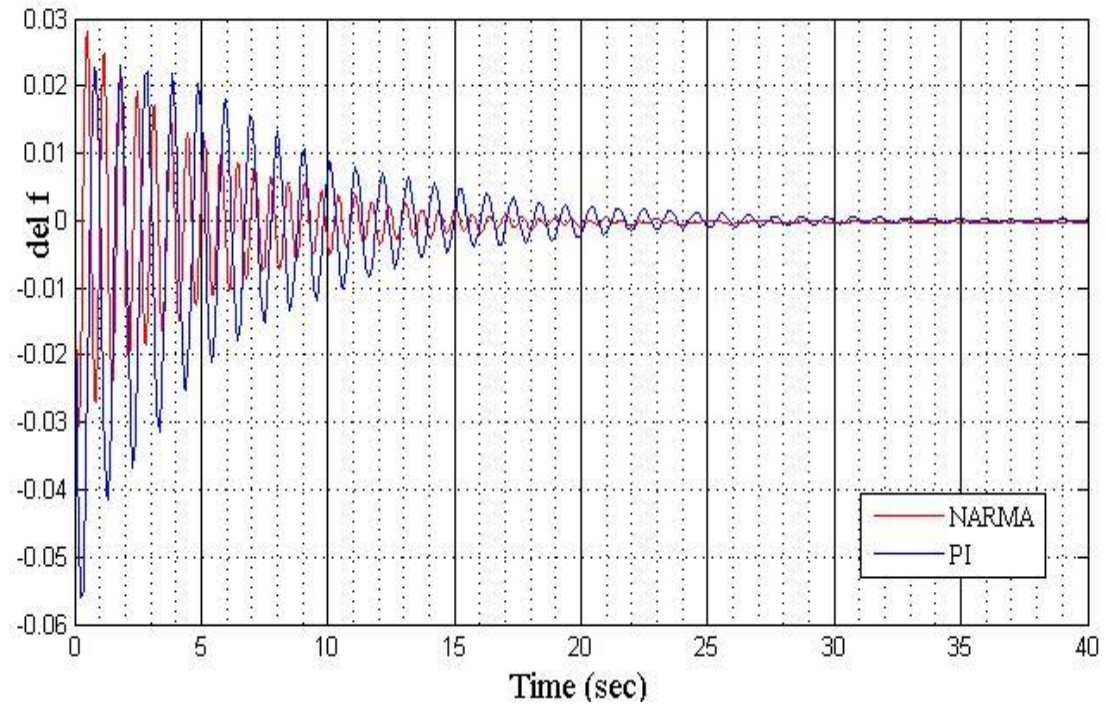


Fig 4.14: Frequency response of area 1 with PI and NARMA L₂ controllers with 5% load change in area 1

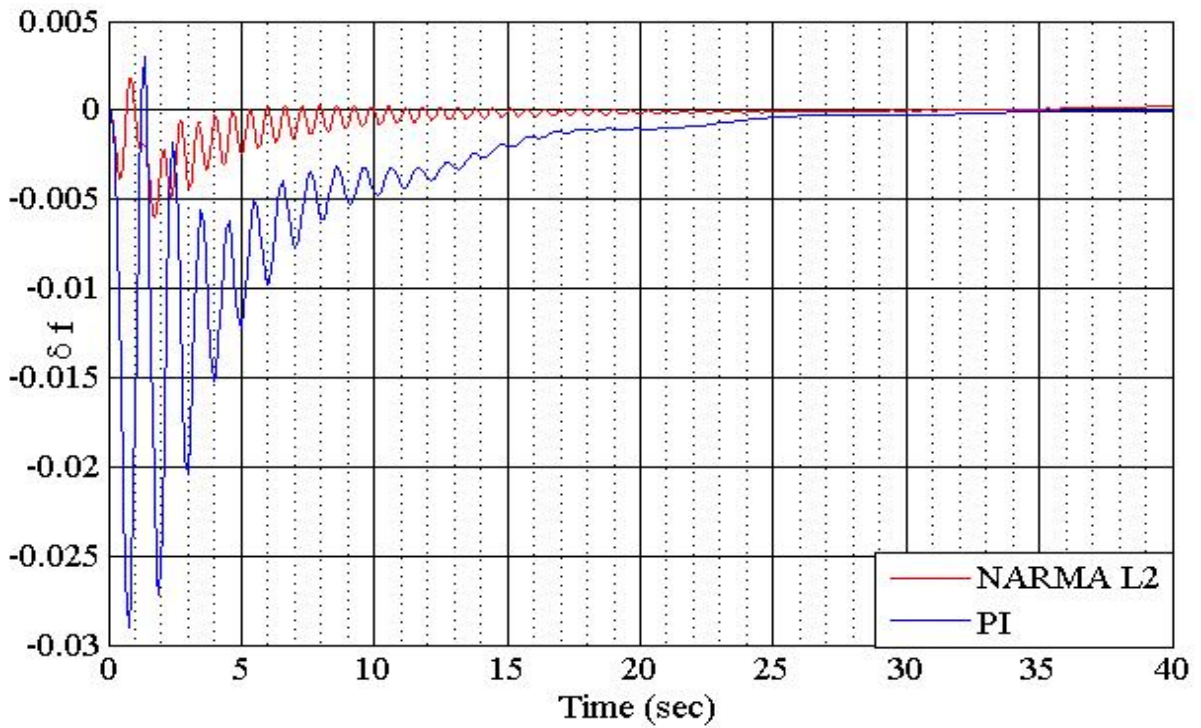


Fig 4.15: Frequency response of area 2 with PI and NARMA L₂ controllers with 5% load change in area 1

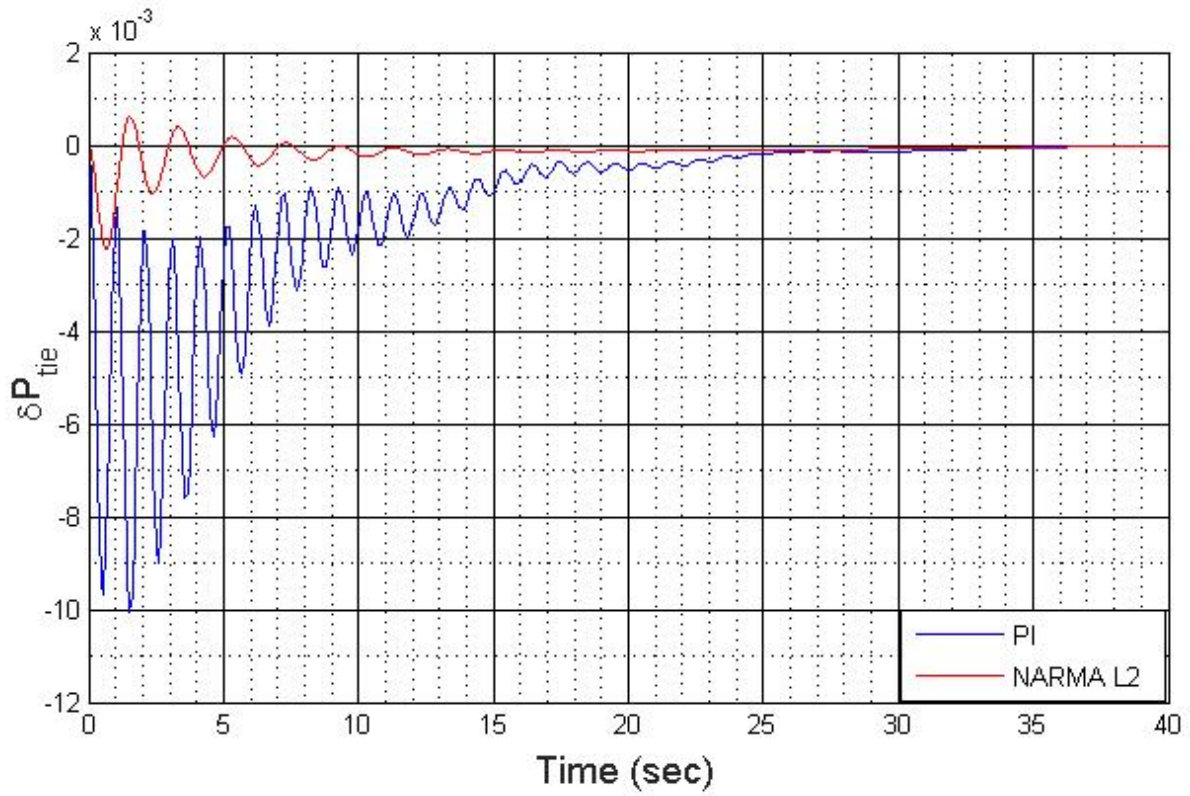


Fig4.16: Tie-line power deviation from area 1 to area 2 with 5% load change in area 1

Table 4.4: Performance comparison of wind integrated power systems with PI and NARMA L2 controllers

LOAD CHANGE	PI CONTROLLER						NARMA L2					
	Area 1		Area 2		Tie-lines		Area 1		Area 2		Tie-lines	
	M_p	t_s	M_p	t_s	M_p	t_s	M_p	t_s	M_p	t_s	M_p	t_s
1%	0.056	18	0.01	33	0.038	34	0.01	6	0.006	17	0.0021	10
5%	0.058	19	0.028	17	0.01	20	0.03	12	0.008	12	0.0025	14

CHAPTER 5

CONCLUSION AND FUTURE SCOPE

5.1 Conclusion

This work recommends neural network based NARMA L2 controller for wind penetrated power system. The training process of ANN based NARMA L2 have been described in details. The model of two area wind integrated system is developed and employed to test robustness of NARMA L2 controlled system following load disturbances. Both PI and NARMA L2 controllers are simulated for two different load changes and results have been plotted.

Two area wind integrated transfer function model with small disturbances has been developed. The conventional PI controller tuned using Ziegler-Nichols method provides satisfactory outcomes for LFC without any non-linearity in the system. However, wind turbines introduce non-linearity in the system which cannot be ignored in LFC problem. Therefore, the intelligent ANN based controller is introduced to tackle the complexity of the control area. The performances of NARMA L2 controller over PI controller have been compared.

The graphical results show NARMA L2 leads in terms of minimizing peak overshoot and settling time. Also, it is important to notice that NARMA L2 reduces settling time with raising system load.

5.2 Future Scope

1. The proposed controller may be considered with real time load frequency control problems.
2. Although wind turbines are used for the primary frequency control it may further used for secondary control as well.
3. The load frequency control can be performed for multi area system with real time data simulation.
4. Load frequency control of wind turbine integrated system can also be considered by other intelligent techniques, i.e. fuzzy logic, ANFIS etc. will be part of future work.

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APPENDIX

$$\Delta P_{L1} \quad 0.01 \text{ p.u.}$$

$$\Delta P_{L2} \quad 0.05 \text{ p.u.}$$

Thermal power plant model parameters

$$K_{g1} = K_{g2} \quad 1$$

$$K_{t1} = K_{t2} \quad 1$$

$$T_{g1} = T_{g2} \quad 0.3 \text{ s}$$

$$T_{t1} = T_{t2} \quad 0.03 \text{ s}$$

$$R_1 = R_2 \quad 2.4$$

$$T_{P1} = T_{P1} \quad 120$$

$$D_1 = D_2 \quad 1$$

$$H_1 = H_2 \quad 20 \text{ p.u.}$$

$$\beta_1 = \beta_2 \quad 0.425 \text{ p.u.}$$

DFIG-based wind turbine model parameters

$$T_{r1} = T_{r2} \quad 0.1 \text{ s}$$

$$T_{w1} = T_{w2} \quad 6 \text{ s}$$

$$R_1 = R_2 \quad 3$$

$$H_{e1} = H_{e2} \quad 20 \text{ p.u.}$$

$$T_{a1} = T_{a2} \quad 0.2 \text{ s}$$

LOAD FREQUENCY CONTRROL

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