MODELING AND CONTROL OF PANTOGRAPH CATENARY SYSTEM

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CERTIFICATE

This is to certify that the project entitled “MODELING AND CONTROL OF PANTOGRAPH CATENARY SYSTEM**”** is an authentic work carried out by Ms.VIDUSHI GUPTA, student of M. Tech., Delhi Technological University, Delhi as her major project in the partial fulfillment of the requirement for the award of the degree of Master of Technology in Power Systems during the year 2014 and it has not been submitted elsewhere for the award of any Degree.

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ABSTRACT

High speed trains permit faster travelling between long distance destinations, making it an easy and comfortable way of travelling. The pantograph is the component of the traction system that collects electrical current from the cable system above i.e. the catenary, to the loco drive system. The interaction between the pantograph and the catenary is the most important factor affecting the quality of energy transmission between the substation and the loco drive system. The current collection enhancement is a key requirement for increasing the speed limit in railway traction system.

As the train speed increases, the interaction between the pantograph and the catenary become more important. The dynamic interaction can cause the variation of the contact force around the mean value. The dynamic contact force variation, superposed to the mean contact force, can cause contact losses, arcing and sparking, with a deterioration of the quality of current collection and an increase of the electrical related wear, thus becoming a limiting factor for the maximum train speed. Hence an optimization of both pantograph and catenary should be carried out in order to improve their performance.

In order to achieve this, a state-space mechanical modeling of an elementary Pantograph-Catenary (PAC) system has been carried out and its electrical analogous model is designed and fabricated. Further, the simulation studies of the PAC system, as an active-control problem, has been carried out in MATLAB-Simulink using design data from the first model work. Here conventional PID and artificial intelligence techniques namely Fuzzy logic, ANFIS, and Fuzzy PID are used for active control of PAC system. All the controllers are then compared in order to minimize the contact force variation.

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INTRODUCTION

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Introduction

Electric railway traction is a green technology which is significantly used for transportation in urban, sub urban areas for very fast land transportation and heavy goods train. The main characteristics of electrification are high efficiency, smooth starting, full driving torque from standstill, compact and simple structure**,** good reliability, low cost drive locos and most importantly regenerative braking but it requires heavy capital expenditure for installation. It basically constitutes of the power transmission lines, including the railway track lines, pantograph-catenary (PAC) system, traction transformer, switch gear and electric drive system.

Firstly 3–phase power from grid is transmitted to the electrical substations at 220kV, 132kV, or 110kV and then the supply is stepped down to 25kV for feeding electric traction catenary system. The AC power from the substation is normally led by two feeder cables or feeders to a feeding post. Each feeder has two conductors, one insulated for 25kV for connection to the bus bar, and the other insulted for a lower voltage (3kV) for connection to the track for the return current. The loco uses a pantograph, a metal structure which can be raised or lowered, to make contact with the overhead contact cable and transfer electrical energy to the loco drive system. The return path for the electricity is through the body of the loco and the wheels to the tracks, which are electrically grounded. Ground connections are provided from the rails at periodic intervals. Traction transformers are used to step down the 25kV voltage level to the required depending upon motor ratings and drive system used. Modern electric locos possess converter inverter system to condition the power fed to the induction motors.

Electric traction is broadly classified as third rail system and overhead catenary system. Third rail is a thick conductor running along the track. Electric traction is operating on AC as well DC. DC supply is preferred in urban, sub urban areas. The DC series motor is universally employed for DC system as its speed-torque characteristics are best suited to traction requirements. Generally low voltage of DC system implies higher current drawn from DC catenary hence require thick and heavy wire resulting in more wear and tear of pantograph catenary system. AC system provides several advantages over DC mainly its maintaining cost is less and it can regenerate power about 15-18% thereby increasing overall efficiency from DC system. The major advantages of 25 kV AC 50 Hz single phase was a light overhead equipment, simple transformer substations located far apart feeding power to rectifier locomotives having tap changer control giving greatly improved adhesion characteristics. The simplified diagram of electric traction system is shown in fig.1.1

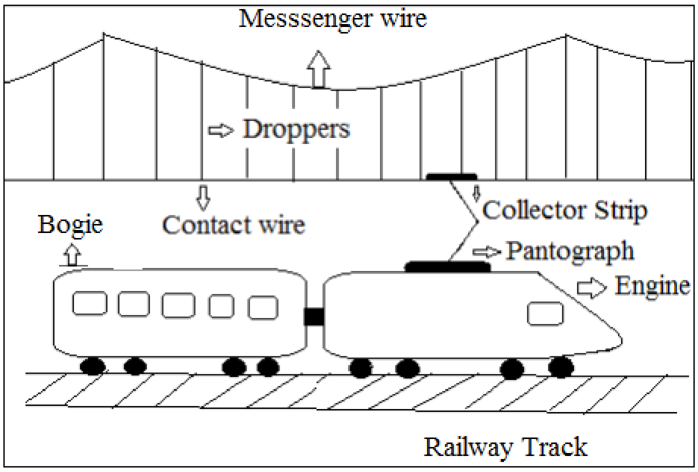


Figure 1.1 Electric Loco Supply system

1.2 Pantograph-Catenary system

PAC system is used for transfer of electrical energy to the drive system. This transfer takes place at the moving interface between the overhead catenary and pantograph and it is the primary function of the designers to ensure the fundamental compatibility of these two systems, and that optimum performance is achieved over a range of weather, speed and maintenance conditions.

Pantograph is a link to collect the current through the contact wire and transfer the same to the electric drive. The head of pantograph is made up of hard carbon for collecting the current and provide lubrication to the messenger wire. Pantograph can be of symmetric or asymmetric type. Double-arm or symmetric pantographs are usually heavier, requiring more power to raise and lower, but may also be more fault-tolerant. The most common type of pantograph is the asymmetric type which has evolved to provide a more compact and responsive single-arm design at high speeds as train gets faster. The design operates with equal efficiency in either direction of motion. The pantograph are designed to operate over a wide range of wire heights, thus it possess two stages namely frame to accommodate gross motion and head for adjustments to follow small fluctuations in wire height.

Catenary constitutes of power conductor namely contact wire, messenger wire and the droppers. The messenger wire is kept in horizontal level to ensure that pan head always remain in contact with contact wire. This is achieved using droppers between the messenger wire and power conductor.

1.2.1 Pantograph Features:

Standard features of present day pantographs are:

- ❖ The DC pantographs generally have two shoes, while the AC pantographs have one shoe, owing to the higher current carried by the DC pantograph.
- ❖ Compressed air is used to raise the pantograph from its resting position to the raised position where its shoes touch the contact wire.
- ❖ The return path for the electricity (the return current) is through the body of the loco and the wheels to the tracks, which are electrically grounded. Ground connections are provided from the rails at periodic intervals. Since the body of the locomotive and the wheels are all metal (steel in most cases) they are quite conductive.
- ❖ Incorporation of an Automatic Dropping Device system designed to lower the pantograph in the case of excessive carbons wear or damage to the pantograph.
- ❖ All pantographs are fitted with aerofoil that must be accurately set to provide sufficient aerodynamic neutrality of the pantograph.

1.2.2 Catenary features:

. The main features of catenary are:

- ❖ Catenary wire is of hard drawn cadmium copper.
- ❖ A tension of 1000 kgs is given in each wire of catenary. This tension is kept constant, automatically compensating the variations in conductor length due to change in temperature through the regulating equipment erected at the termination of conductors, also known as Automatic Tensioning Device. The catenary span varies between 72m and 27m with a step of 4.5m depending upon the wind pressure. In this study the catenary span is considered to be 63 Meters.
- ❖ Before designing the Power Supply arrangements and the type of overhead equipment of a section, a choice is required to be made whether conventional 25 kV system is to be adopted or 2 X 25 KV Auto Transformer system is to be adopted. This choice

depends upon a number of factors viz. the sections to be provided with booster transformers and return conductor, the demand of power for the volume and type of the traffic and suitable location available for traction substations.

- Catenary may be of simple or complex type. A single wire or trolley wire is for low speed below 50km/hr. Simple catenary consist of messenger wire, droppers and contact wire. Complex catenary may be of stitched or compound type. Stitched is similar to simple catenary but an additional wire is tied from messenger wire bypassing each support tower for uniform stiffness. Different type of catenary system is shown in fig 1.2.

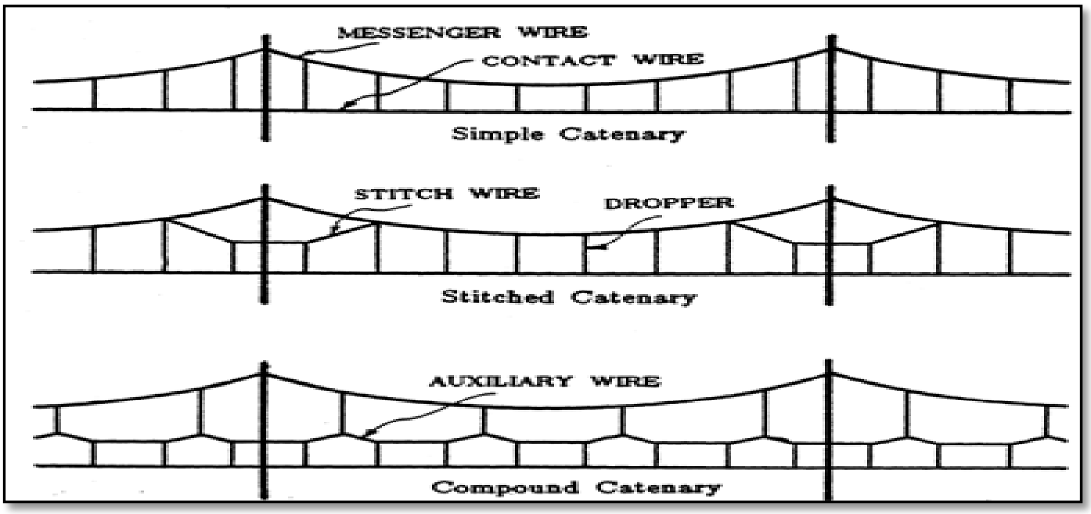


Figure 1.2: Different types of Catenary

1.3 Motivation

In the recent trends more number of high speed trains are required as it provides time efficient operations. Hence pantograph catenary system plays a major role in todays traction system.

Here in this study the main focus is kept on to minimize the contact force oscillations thereby reducing the probability of loss of contact.To better understand the dynamic interaction of PAC system a mechanical model is developed and then its electrical analog is synthesized in the laboratory. The work is been concentrated such that the oscillations resulting from interaction of pantograph-catenary system are minimized. Hence intelligent controllers are designed for this system. Due to the difficulty of parameter setting and changing related to the system conditions for PID controllers, the intelligent controllers are preferred.

1.4 Dissection of thesis

The whole work of dissertation is organized in total 7 chapters.

Chapter1 presents the general introduction of the Electric traction system, Pantograph Catenary system and objective of thesis.

Chapter 2 contains the literature review of the pantograph catenary system, its modeling and control techniques used so far.

Chapter 3 elaborates a mathematical modeling of pantograph-catenary system (PAC). In this chapter an electrical analogous model is synthesized, and a reduced order modeling of transfer function is also given.

Chapter 4 discusses the design of electrical hardware prototype of PAC system and its results are validated with respect to mechanical model.

Chapter 5 describes the active control of PAC system. All the controllers namely PID, Fuzzy Logic Control, Fuzzy PID, and ANFIS are designed for active control of PAC system and simulated using MATLAB simulink**.** Different control blocks are explained in this chapter.

Chapter 6 contains the simulink results for the active PAC system. The results are presented and analyzed in this chapter.

Chapter 7 contains the conclusions based on the hardware and simulink results. It also includes the further scope of the work done.

1.5 Conclusion:

In this chapter a brief about Electric Traction and its components have been discussed. The PAC system and its important characteristics are discussed here. Further, the motivation about the problem formulation and the relevant problems in the PAC system are detailed. This chapter also provides a quick look of the topics discussed in the thesis/dissertation.

CHAPTER II

LITERATURE OVERVIEW

CHAPTER II
LITERATURE OVERVIEW

Introduction

In this chapter a brief literature review about PAC system is presented. All the models of the PAC system are discussed thoroughly. This chapter presents the basis of work done further.

2.2 Pantograph-Catenary System Studies

The pantograph-catenary system is a dynamically coupled system. A pantograph is a mechanical arm mounted on the roof of locomotive and used to collect the electric power from overhead catenary system. When the train starts the pantograph head is maintained in contact with overhead wire through a static uplift force. As the train speeds up, the vibration in the catenary increases, thereby resulting in loss of contact, arcing, deterioration of quality of current collection and wear of catenary.

Ideally pantograph should touch the wire hard enough for maintaining electrical contact but also it should be light enough for lesser significant displacement of catenary. The increase of the static uplift force is not an efficient way to solve the problem, because it increases mechanical abrasive wear and large catenary displacements resulting in loss of contact [1]. Its interaction also affects the electromagnetic interference.

Different numerical approaches exist in the literature to handle the pantograph-catenary interaction. In 1955, French National Railways (SNCF) demonstrated that 25 KV single phase, 50 cycles (Industrial Frequency) A.C. system is superior to other types of Electric Traction. Studies on overhead equipments for railway traction electrification at 25 kV AC were initiated around 1966. Willets and Edward [2] assembled a scaled model of Standard British railways PAC system and observed that complex pantograph movements develop at quite low speeds. Also the serious loss of contact occurs when there is an abrupt change occurs in the trajectory of catenary, mainly at the equipment support. G. Gilbert [3] shows mathematically that by increasing sag in the contact wire the number of droppers can be reduced thereby improving economy of the system and that increasing the total conductor tension will increase the critical speed and further TA Willets [4] confirmed it experimentally. Boissonnade and Pierre recommended for one way damping i.e. resistance only to the downward direction for contact lossless PAC system [5]. In consideration of passive pantograph many researchers suggest lighter pan head but Wann proposes that the influence of lower sprig is more important than lighter pan mass and larger damper [6]. Connor conducted time domain and frequency domain analysis of one and two pantograph-catenary system. He supported all- aluminum catenaries than copper and requirement of small amount of sag in the catenaries [7].

2.3 Pantograph Catenary Modeling Review

Many studies developed the mathematical model for PAC system with single, two and three degree of freedom using different parameters for better understanding of the dynamic interaction of PAC system [8]-[16]. A periodically excited single degree of freedom (SDOF) model representing the basic dynamics of the combined PAC system has been proposed by Wu and Brennan [9]. In this system, the mass of the catenary is neglected and complete pantograph is modeled as a whole mass. Two degree of freedom model was proposed by S.D. Eppinger [17] et al with pantograph modeled as linear two mass system consisting of the head mass and the frame mass and catenary is modeled using modal analysis. 3DOF with pantograph consisting of three masses mainly head, upper frame and lower frame and catenary is represented by variable stiffness [18]. It was shown that two degree of freedom models have been appropriate to represent a number of symmetric pantograph designs and an additional degree of freedom representing frame dynamic has been added to represent the asymmetric designs.

However, no researcher has tried to develop the prototype electrical model of PAC system. A first prototype of servo-actuated pantograph is developed by B. Allotta et al [19] and some simulation and experimental results were obtained. A. Balestrino [20] have proposed a modified pantograph model by adding wire simulation, in order to exert a constant force the moving pantograph and overhead wire. Liu et al [21] presented an extended Mayr's equation-based model for the pantograph detachment arc of the high-speed railway traction system. Multibody models of pantographs have also been discussed by many researchers. These models give more realistic simulation results and help to perform any modifications and new design concepts based on dynamic simulation [22]-[24].

Kia et. al. [25] presented a review of different models of PAC system in theory. He presented three models namely simple, Euler-Bernoulli-Timoshenko model and using modal analysis for catenary and concluded that with low speed constant catenary can be taken in account and under high speed condition wave propagation impact becomes vital thus FEM based on Euler-Bernoulli-Timoshenko beam model gives more precise results but for reducing calculation burden modal analysis is preferred .

R. Garg et al has carried out the sensitivity analysis of PAC system model [26] and it was found that the system is most sensitive with respect to the mass of frame, head mass and damping coefficients during dynamic operating conditions but under steady state the system sensitivity varies only wrt spring constants. The quality of current collection by the pantograph depends upon the contact pressure between the pantograph head and speed of the train [27].

Most of the models discussed above are mechanical models. These models are analyzed through simulation. Electrical analogous of this model is not available in the literature.

2.4 Control of PAC System

The loss of contact between pantograph-catenary interface is a major limitation for high speed traction system. This loss of contact can be avoided by increasing the contact force but it results in large wear and tear on the system. Hence the loss of contact is minimized using active pantographs. Active pantographs have the quality of improving the current collection by reducing the variation in the force by providing closed loop control.

Previously, many researchers have stated the concept of active pantograph system and designed controllers for it [28]-[37]. O. Connor et al were one of the pioneers in designing active control for high speed pantograph. They have derived the control law for the active proportional controller which requires only a single measurement ie difference between the head and frame height [28]. A. Pisano et al [30] have regulated the contact force in active train pantographs with the help of wire actuators using second order sliding mode based control scheme. They have also proposed a solution based on proper combination between real time robust differentiators (high gain observers) and robust controllers (second order, sliding mode controllers). B. Allotta et al [31] have designed and experimentally verified the complete layout of the control strategy for the PAC system. S. Walter [32] has designed and compared the performance of PID controllers and fuzzy PD and integral controllers and observed that both the controllers have same type of response. An adaptive fuzzy logic controller is also designed, representing the catenary by a constant stiffness [33]. R. Garg et al has carried out the sensitivity analysis of PID controller parameters for pantograph-catenary (PAC) system [34] and it was found that the system is most sensitive with respect to the proportional gain and time integral of the PID controller. Also, the system becomes more sensitive at higher frequency of oscillations.

2.5 Conclusion

This chapter presents the literature survey of the PAC system, its modeling and control. This helps in gaining the fundamental knowledge of the system and also presents an overview of the research work done so far.

CHAPTER III

PAC SYSTEM MODELLING AND MODEL ORDER REDUCTION

CHAPTER III

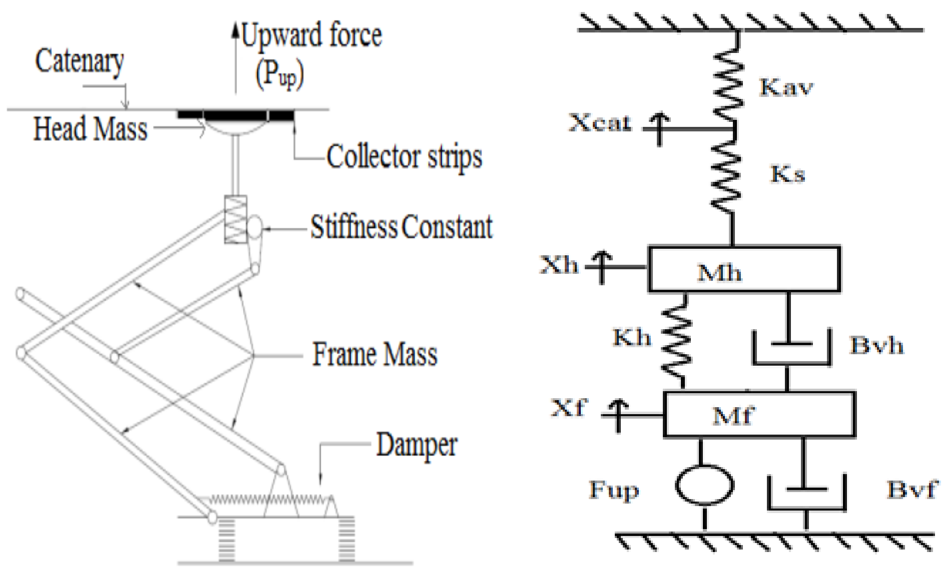
PAC SYSTEM MODELING AND MODEL ORDER REDUCTION

Introduction

This chapter deals with the modeling of pantograph-catenary system. Initially mechanical model is developed and described and then further synthesized electrical analogous model is detailed. Models with high order are required in order to provide more accurate description of a dynamic system but they result in increased order of complexity of the system. Hence a reduced order modelling of the system is presented further.

3.2 Mechanical Modeling of PAC System

Pantograph is an important link to transfer the power from the power conductor to loco transformer. Constant pressure is applied at the head of the pantograph through pneumatic control mechanism to ensure that it always remain in contact with the contact wire. The pantograph mechanism is shown in Fig 3.1(a) and it is represented by the 2 degrees of freedom mechanical system in Fig 3.1(b). Here the inertia force of the pantograph is neglected.



(a) (b)

Figure 3.1 4^{th} order Mechanical modelling of Pantograph

3.2.1 Modeling of Pantograph

The pantograph is modelled as a set of masses, springs and shock absorbers. The pantograph shown is of asymmetric design consisting of head and frame structure. The frame uses a pneumatic air cylinder for its suspension and head is mounted to the frame through a torsional spring as suspension. The contact between the head of the pantograph and the catenary is represented by a spring. The displacement of power conductor is the function of force on the power conductor due to pantograph.

It is assumed that complete pantograph moves as a rigid body and the pantograph catenary system can be represented by the two degrees of freedom of mechanical system.The upper mass represents the head M_h while mass of frame is represented by lower mass M_f. K_s represent the combined stiffness of the contact strips and pantograph shoe, K_{av}, represents the stiffness of catenary and K_h is the stiffness between the head and the frame. B_{vf} and B_{vh} are the linear one- way damping elements. F_{up} is the constant uplift force exerted by the pneumatic cylinder on the frame.

3.2.2 Modeling of Catenary

The catenary comprises of messenger wire, dropper and contact wire. The stiffness of the catenary is not constant over the span. In the centre of the span, the catenary is soft hence the stiffness reduces as compared to the stiffness near the support of the tower. The stiffness variation of the overhead wire in a given span is the primary cause of vibration in PAC system. But in order to reduce complexity only constant static stiffness is considered for catenary. It is assumed that the configuration of catenary is simple and the effect of initial sag and aerodynamic force is neglected.

It is supported at the supporting towers placed at some distance apart. The stiffness of the catenary is not constant over the span. In the centre of the span, the catenary is soft and it has more stiffness near the support of the tower. So, the catenary is represented by the time varying stiffness, K(t), given by (3.1), which depends on the length of the span, L, and speed of the train, V,

$$K(t) = K_0[1 + \alpha \cos(\frac{2\Pi V}{L})\, t] \qquad (3.1)$$

and

$K_0 = \frac{1}{2}\,(K_{max} + K_{min})$ and $\alpha = \frac{K_{max} - K_{min}}{K_{max} + K_{min}}$, where Kmax and Kmin are the maximum and minimum stiffness of the catenary in a span respectively and is the stiffness variation coefficient along the span.

Due to unequal stiffness of the catenary, the pantograph will be subjected to upward and downward oscillations while moving. The magnitude of these oscillations will depend upon the speed of the vehicle and the variation in the stiffness of the catenary along the span. For very high speeds, upward vibration at the mid span may be so light that inertia forces make the pantograph pan leave the contact of catenary. For good current collection, it is not only necessary that stiffness within the span should be high but its variation should be small.

3.2.3 PAC System Equations

The pantograph and catenary model are coupled through K_s. The force through the compressed spring K_s is the contact force. If at any point in simulation the spring becomes tensioned, the contact force is set to zero. A tensioned spring signifies loss of contact.

X_{cat} is the displacement of catenary. For the system shown in Fig.4, the equation of motion of the catenary pantograph model is written in the form of simple, second-order differential equation as given by (3.2) and (3.3),

$$M_h \frac{d^2X_h}{dt^2} + K_h(X_h - X_f) + B_{vh}\left(\frac{dX_h}{dt} - \frac{dX_f}{dt}\right) + K_s(X_h - X_{cat}) = 0 \qquad (3.2)$$

$$M_f \frac{d^2X_f}{dt^2} + K_h(X_f - X_h) + B_{vh}\left(\frac{dX_f}{dt} - \frac{dX_h}{dt}\right) + B_{vf}\frac{dX_f}{dt} + K_h(X_f - X_h) = F_{up} \qquad (3.3)$$

The state space equations are given as (3.4)-(3.5)

$$\dot{x} = Ax + Bu$$

$$= \begin{bmatrix} 0 & 1 & 0 & 0 \\ \frac{1}{M_h}\left(\frac{k_s^2}{(k_s+k_{av})} - (k_s + k_h)\right) & -\left(\frac{B_{vh}}{M_h}\right) & \left(\frac{k_h}{M_h}\right) & \frac{B_{vh}}{M_h} \\ 0 & 0 & 0 & 1 \\ \frac{k_h}{M_f} & \frac{B_{vh}}{M_f} & -\left(\frac{k_h}{M_f}\right) & -\left(\frac{B_{vh}+B_{vf}}{M_f}\right) \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{1}{M_f} \end{bmatrix} [F_{up}] \qquad (3.4)$$

$$Y(s) = Cx(s) + Du(s) \quad = \left[\left(\frac{K_s}{K_s+K_{av}}\right) \quad 0 \quad 0 \quad 0\right]\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + [0] \qquad (3.5)$$

where the input state space variables are:

$X_1(s) = X_h(s)$, $X_2(s) = \dot{X_1}(s) = \dot{X_h}(s)$, $X_3(s) = X_f(s)$, $X_4(s) = \dot{X_3}(s) = \dot{X_f}(s)$

and the output variable is

$Y(s) = X_h(s) - X_{cat}(s)$

Using state apace equations and substituting the values of parameters given in Table 3.1 in (3.4) and (3.5), the open loop transfer function is given by (3.6), and the contact force is given by (3.7)

$$G(s) \quad = \frac{X_h(s)-X_{cat}(s)}{F_{up}(s)}$$

$$G(s) = \frac{s+53.8}{1.27s^4+29.92s^3+12412.67s^2+132628.28s+4.43\times10^6} \qquad (3.6)$$

$$F_c(s) = K_s[(X_h(s) - X_{cat}(s)] \qquad (3.7)$$

TABLE 3.1

DEFINED PARAMETERS FOR PAC SYSTEM

S No	Quantity	Parameter	Typical Value	Units
1.	M_h	P head mass	9.1	kg
2.	M_f	P Frame mass	17.2	kg
3.	K_h	P head spring coefficient	7 x 10^3	Nm-1
4.	K_s	P shoe spring coefficient	82.3 x 10^3	Nm-1
5.	K_{av}	Average cat spring coefficient	1.535 x 10^6	Nm-1
6.	B_{vh}	P head damper coefficient	130	Nm-1s
7.	B_{vf}	P frame damper coefficient	30	Nm-1s
8.	F_{up} (constt)	Upward force exerted	100	N

3.3 Electrical Analogous Model

Mechanical systems are analogous to electrical systems. They have three passive, linear components. Two of them, spring and mass, are energy storage elements and the third, viscous damper, dissipates energy. The two energy storage elements viz. spring and mass are analogous to two electrical energy storage elements viz. inductor and capacitor. Energy dissipating element viz. viscous damper is analogous to electrical resistance.

Using force-voltage analogy, where the mechanical force is considered analogous to the electrical voltage, mechanical velocity is analogous to the electrical current or mechanical displacement is represented by the charge, spring is analogous to the capacitor, the viscous damper is analogous to the resistor and the mass is analogous to the inductor. Thus, summing forces, written in terms of the velocity, is analogous to the summing voltages, written in terms of the current, and the resulting mechanical differential equations are analogous to mesh equations.

Using above analogy, the above mechanical model can be represented by electrical parameters as given in Fig. 3.2.

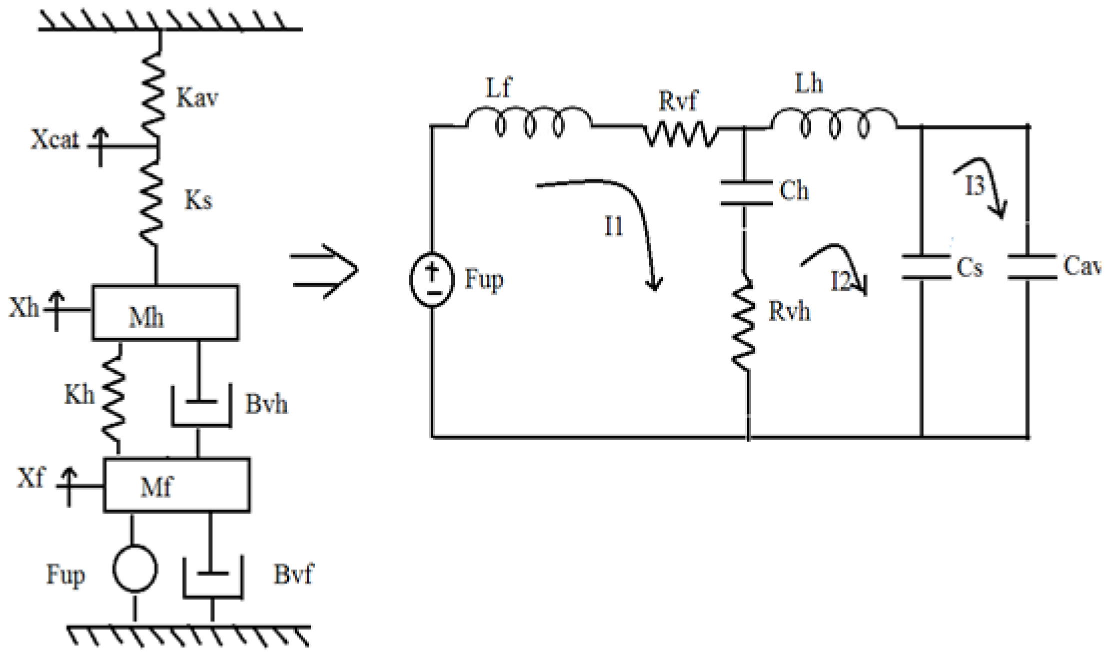


Figure 3.2: Equivalent Electrical Analogous Model

Here the equations for electrical analogous model second-order differential equation are given by (3.8) and (3.11), and the state space equations are given as (3.12)-(3.13):

$$\dot{X}_1(s) = X_2(s) \quad (3.8)$$

$$\dot{X}_2(s) = X_1(s)\left[\left(\frac{C_s+C_{av}+C_h}{L_hC_h(C_s+C_{av})}\right)\right] - X_2(s)\left[\frac{R_h}{L_h}\right] + X_3(s)\left[\frac{1}{L_hC_h}\right] + X_4(s)\left[\frac{R_h}{L_h}\right] \quad (3.9)$$

$$\dot{X}_3(s) = X_4(s) \tag{3.10}$$

$$\dot{X}_4(s) = X_1(s)\left[\frac{1}{C_h L_f}\right] + X_2(s)\left[\frac{R_h}{L_f}\right] - X_3(s)\left[\frac{1}{C_h L_f}\right] - X_4(s)\left[\frac{R_h+R_f}{L_f}\right] + V_i(s)\left[\frac{1}{L_f}\right] \tag{3.11}$$

And the relevant state space equations are given by (3.12)-(3.13)

$\dot{X}(s) = Ax(s) + Bu(s)$

$$\dot{X}(s) = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -\left(\frac{C_s+C_{av}+C_h}{L_h C_h (C_s+C_{av})}\right) & -\left(\frac{R_h}{L_h}\right) & \left(\frac{1}{L_h C_h}\right) & \frac{R_h}{L_h} \\ 0 & 0 & 0 & 1 \\ \frac{1}{C_h L_f} & \frac{R_h}{L_f} & -\left(\frac{1}{C_h L_f}\right) & -\left(\frac{R_h+R_f}{L_f}\right) \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{1}{L_f} \end{bmatrix} [V_i] \tag{3.12}$$

$Y(s) = Cx(s) + Du(s)$

$$Y(s) = \left[\left(\frac{C_s - C_{av}}{C_s}\right) \quad 0 \quad 0 \quad 0\right] \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + [0] \tag{3.13}$$

where input state variables are

$X_1(s) = Q_2(s), \; X_2(s) = I_2(s) = \dot{X}_1(s), \; X_3(s) = Q_1(s), \; X_4(s) = I_1(s) = \dot{X}_3(s)$

And the output state variable is

$Y(s) = Q_2(s) - Q_3(s) = V_0(C_s - C_{av})$

Using these state space equations and substituting the values from Table 3.2, the derived transfer function of the electrical analogous model is given in equation (3.14).

TABLE 3.2:

CALCULATED PARAMETERS FOR ELECTRICAL ANALOGOUS MODEL

S No	Quantity	Parameter	Typical Value	Units
1.	L_h	P head mass	9.1	H
2.	L_f	P Frame mass	17.2	H
3.	C_h	P head spring coefficient	143*10^-6	F
4.	C_s	P shoe spring coefficient	12*10^-6	F
5.	C_{av}	Average cat spring coefficient	0.65x 10^-6	F
6.	R_{vh}	P head damper coefficient	130	ohm
7.	R_{vf}	P frame damper coefficient	30	ohm
8.	V_{up}	Upward force exerted	100	V

Here we observed that the transfer function thus obtained using electrical parameters i.e.:

$$G(s) = \frac{Q_2 - Q_3}{V_i} = \frac{s+53.7}{1.29s^46+31.00s^3+1.3e004s^2+1.2e005s+4.5e006.} \quad (3.14)$$

is approximately the same as that of mechanical model.

3.4 Model Order Reduction of the PAC System

Models with high order are required in order to provide more accurate description of a dynamic system but also they results in increased order of complexity of the system. Further, the transfer function is reduced to lower order for lesser complexity, reduced time consuming calculations, analysis and designing efforts. Here, PAC model with the two degree of freedom having fourth order transfer function is considered and the transfer function for displacement derived previously in equation (3.6) is used. The model is reduced such that it retains its stability and the output is approximately the same as the original higher order model. Later the transfer functions are simulated using MATLAB and their responses are compared with the original transfer function response. These studies are not available in the literature so far for PAC system

A higher order control system may contain poles with lesser impact on the system response. Hence it is important to sort out the poles having dominant effect on the transient response of the system and reduce the order of the system. The basic idea of reduced order modeling is to replace a given system by a system possessing the same crucial properties like stability, passivity but with smaller state space dimensions [38]-[41]. Here, two methods are applied to reduce the order of the PAC system namely:

a. Approximation of higher order system by lower order system
b. Order Reduction Using MATLAB Programming

3.4.1 First Method: Approximation of higher order system by lower order system

This method preserves stability in the reduced model, if the original high-order system is stable. Thus it ensures the matching between the original higher order and lower order systems for impulse, step and ramp inputs.

Let the higher order system transfer function be represented by (3.15),

$$M_H(s) = K\frac{1+b1s+b2s^2+\cdots+bms^m}{1+a1s+a2s^2+\cdots+ans^n} \quad (3.15)$$

where $n \geq m$.

Let the transfer function of the approximating low order system be given by (3.16),

$$M_L(s) = K\frac{1+c1s+c2s^2+\cdots+cqs^q}{1+d1+d2s^2+\cdots+dps^p} \quad (3.16)$$

where $n \geq p \geq q$.

Here the zero frequency gain K of two transfer function is same. This will ensure that the steady state behaviour of higher order system is preserved in the low order system. Furthermore we assume that the poles of $M_H(s)$ and $M_L(s)$ and are all in the left half of s-plane, since we are not interested in unstable system. The transfer functions $M_H(s)$ and $M_L(s)$ generally refer to the closed loop transfer function, but if necessary, they can be treated as open loop transfer functions.

The criteria of finding the low-order $M_L(s)$, is to satisfy the following condition as closely as possible when $M_H(s)$ is given by (3.17),

$$\frac{|M_H(j\omega)|^2}{|M_L(j\omega)|^2} = 1 \quad (3.17)$$

for $0 \leq \omega \leq \infty$

Also the amplitude characteristic of the two system in the frequency domain ($s = j\omega$) are similar. Thus it will lead to similar time response for two systems. The approximation procedure involves the following two steps:

1. Choose the appropriate orders of the numerator polynomial, q, and denominator polynomial, p, of $M_L(s)$ in (3.15).
2. Determine the coefficients c_i, i = 1, 2,.. q, and d_j, j= 1, 2, …p, from (3.16) so that the condition given in (3.17) is approached.

The gradient vector is used according to the difference areas between the original and reduced model. A positive gradient indicate upward direction and negative gradient indicate downward direction. When the output error reaches the minimum the system is then said to be stable and the reduced transfer function will be the optimal approximation of higher order system.

Using this approximation as given above, the new reduced transfer function of (3.6) is reduced to second order as given by (3.18),

$$G(s) = \frac{1.21+1.21s}{14000s^2+112300s+10^5} \tag{3.18}$$

3.4.2 Second Method: Order Reduction Using MATLAB Programming

This method is implemented in MATLAB m-file. It retains the original characteristics of the higher order model. The reduction procedure is simple compared to other conventional techniques and the error is also minimized.

Following are the steps to be followed for model order reduction using MATLAB:

Step 1: Load the higher order transfer function and determine the size, dominant poles and zeros using bode plot.

Step 2: Plot the Hankel Singular value plot for examining the relative energy per state of original transfer function. States with relatively small Hankel singular values can be safely discarded.

Step 3: Mention the order of lower order system.

Step 4: Determine the coefficients of reduced order system using MATLAB.

Step 5: Plot the response of the reduced order system.

The fourth order model is reduced to 3rd, 2nd and 1st order model and these results are then compared with the original transfer function. The transfer functions after order reduction are as follows:

Transfer function for 3rd order is given by (3.19),

$$G(s) = \frac{0.2269s+12.54}{s^3+2737s^2+2.305e004s+1.032e006} \qquad (3.19)$$

Transfer function for 2nd order is given by (3.20),

$$G(s) = \frac{0.004603}{s^2+8.254s+378.8} \qquad (3.20)$$

Transfer function for 1st order is given by (3.21),

$$G(s) = \frac{0.001279}{s+105.3} \qquad (3.21)$$

3.4.3 Simulation of the reduced order transfer functions

All the transfer functions obtained above as given in (3.6) and (3.18)-(3.21), are simulated in MATLAB as shown in Fig.3.3.The the contact force from (3.7) is plotted in Fig. 3.4.

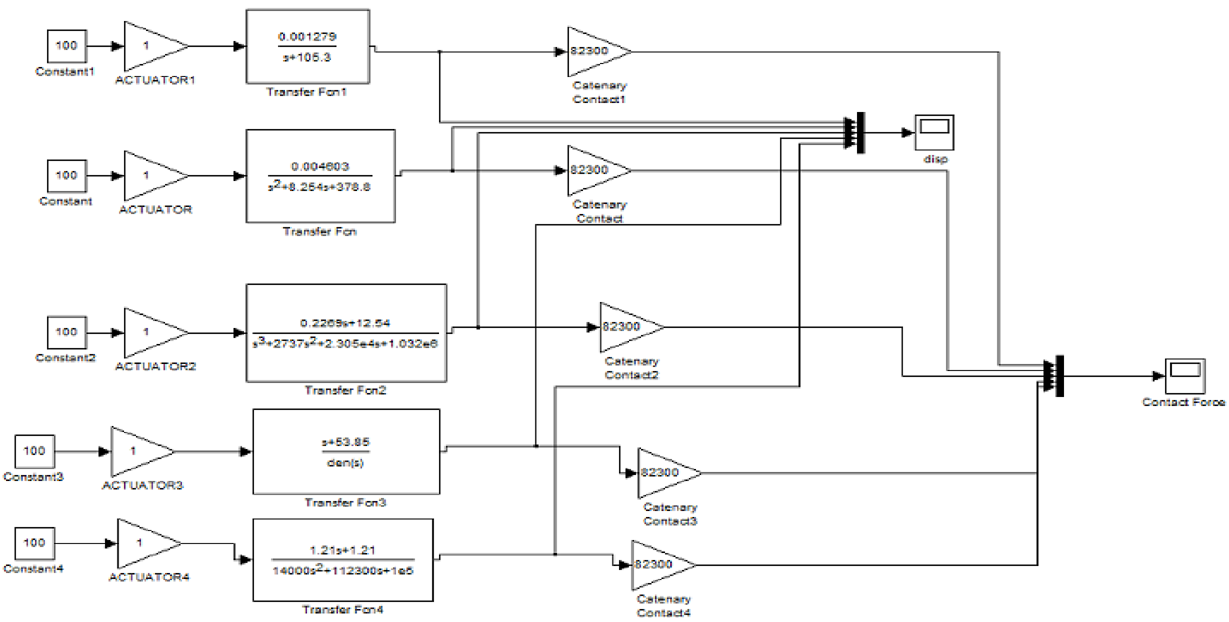


Figure 3.3 The simulink model for original and reduced order transfer functions**.**

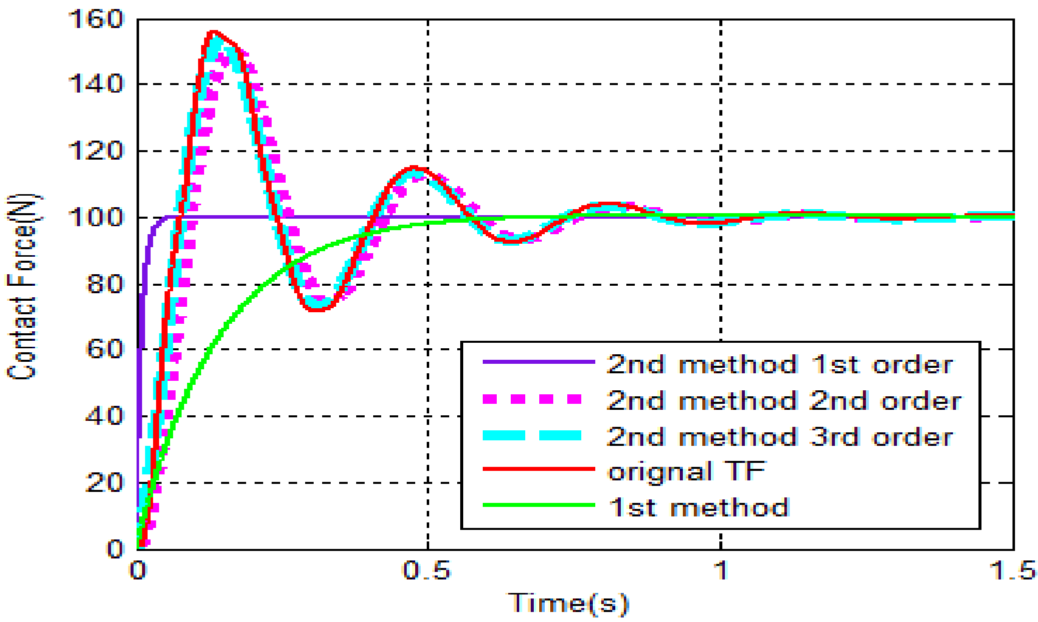


Figure 3.4 Contact force of the original and the reduced order transfer functions

The output of the original and the reduced order transfer functions is shown in fig 3.4. The response from the first method namely approximation of higher order by lower order system gives critically damped results with very high settling time (T_s) and no overshoot (M_p). The result of first order transfer function (TF) of second method namely MATLAB programming method gives critically damped results with very less settling time and no overshoot. The second and third order TF possesses approximately the same response with same overshoot and settling time. The Integral Square Error (ISE) is calculated for all the lower order models in respect of the original model. In view of ISE, it can be stated that the transfer function obtained by 3rd order using MATLAB programming gives the minimum error. Table 3.3 shows the comparison of both the methods with respect to peak overshoot, settling time and ISE.

TABLE 3.3

COMPARISON OF ALL THE REDUCED ORDER MODELS

Parameters	Original Model	1st method	2nd method		
		2nd order reduction	1st order reduction	2nd order reduction	3rd order reduction
M_p (%)	56	-	-	50.5	54
Ts(s)	1.2	0.7	0.08	1.25	1.2
ISE	0	0.21	0.0058	2.38e-004	3.74e-004

Here the overshoot is smaller in the second order model obtained using MATLAB programming method in comparison with original transfer function, but it is observed that second order reduction gives small ISE. So reduced second order model gives the good approximation of the original transfer function with reduced complexity. It can be inferred from the comparison table that the second order transfer function obtained using MATLAB programming method can be best approximated to the original PAC model with minimum ISE.

3.5 Conclusion

This chapter presents the basic 2DOF model of pantograph catenary system and its analysis for deriving the transfer function. Further the synthesized Electrical Analogous Model is described and its transfer function is derived using state space analysis and verified with the mechanical model. Last part of this chapter describes model order reduction techniques and its benefits and then reduced order transfer functions of PAC system are derived. Here two techniques were presented and the responses were compared using Integral Square Error.

CHAPTER IV

ELECTRICAL HARDWARE SETUP AND VALIDATION OF RESULTS

CHAPTER IV

ELECTRICAL HARDWARE SETUP AND VALIDATION OF RESULTS

Introduction

This chapter presents the hardware setup of the electrical prototype of PAC system. Firstly the hardware set up is explained thoroughly. Then its simulink model results are compared with the hardware output and thus the results are verified.

4.2 Hardware Setup of Electrical Prototype Model

Fig 4.1 shows the hardware setup of the electrical analogous circuit. The hardware set up comprises of a electrical prototype hardware, a Tektronix TDS 2014B four channel digital storage oscilloscope, 100 Hz, 1GS/s, a dual output DC regulated power supply of ± 12V, a Tektronix AFG3021B Signal Generator. Here the prototype is assembled on PCB in DTU, laboratory. The circuit contains op amp IC 741 for simulated inductance, electrolytic capacitors and resistors.

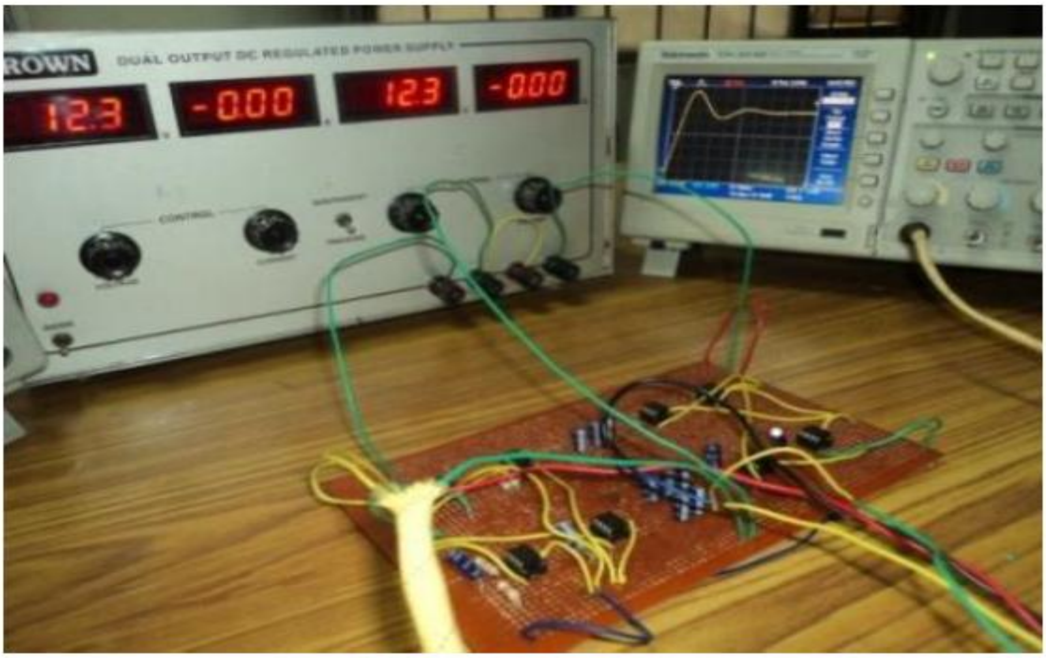
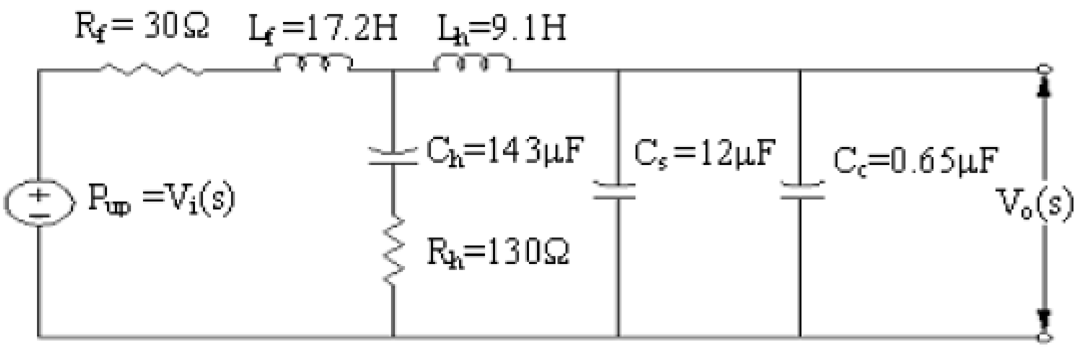


Figure 4.1 Hardware setup of the Electrical Prototype of PAC System

4.2.1 Floating Inductor Realisation

In the electrical hardware model we are using two simulated inductors as shown in fig 4.2 of values ‘17.2 H’ and ‘9.1H’. Both of these inductors are of floating type as none of their end is connected to ground.Electrical inductor is bulky and costly but, reducing the size of the inductors reduces the quality factor. There is also a fundamental limitation of using electrical inductor that it cannot be suitable for the micro miniature structure and integrated circuits applications. Because of these limitations, electrical inductor cannot be used in most of the electronic circuit applications. Hence simulated inductors are used as an alternative. In case the simulated inductor becomes floating, the simulated circuit for replacement of inductor will be different.

It can be realized using op amp ICs through different circuits available for floating inductor in different papers [42]-[47]. The inductors are realized using Antoniou’s inductance circuit as shown in fig 4.3 [42].



$V_i(s)=P_{up}$, $R_f=B_{vf}$, $L_f=M_f$, $C_h=1/K_h$, $R_h=B_{vh}$, $C_s=1/K_s$, $C_c=1/K_c$.

Figure 4.2 Electrical Prototype of PAC system

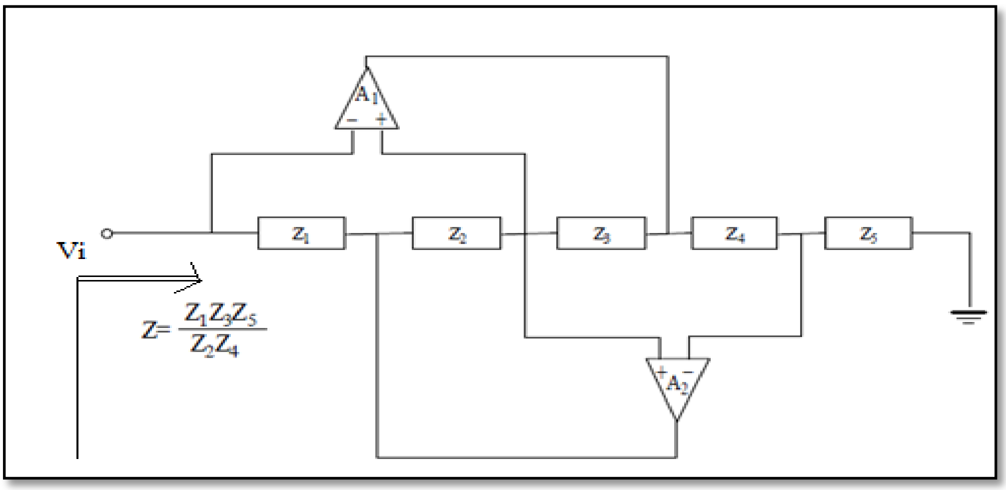


Figure 4.3 The Antoniou’s Floating Inductor Circuit

The GIC circuit, invented by A. Antoniou in 1969, is very tolerant of op amp non-ideal properties, i.e. in particular finite gain and bandwidth. The above circuit is used for grounded inductance realization. The realization of floating inductor is done using two gyrators back to back i.e. cascaded. The resulting Floating GIC circuit is shown in fig 4.4. In this circuit we will use four op amps, seven resistors of identical rating and two capacitors of same ratings. A Generalized Impedance Converter (GIC) consists of NA active circuit elements and NP passive impedances Zk, k = 1, 2 … NP, where NP is (with only a few exceptions) an odd number.

$$Z_{in} = \pm \frac{Z1}{Z2}\frac{Z3}{Z4} \dots \dots \frac{Z_{NP-2}}{Z_{NP-1}} Z_{NP} * Z_{NA} \quad (4.1)$$

The positive/negative sign in (4.1) appertains to the positive/negative impedance converter. The input terminals, between which the impedance is measured, can be either floating or one of them is grounded.

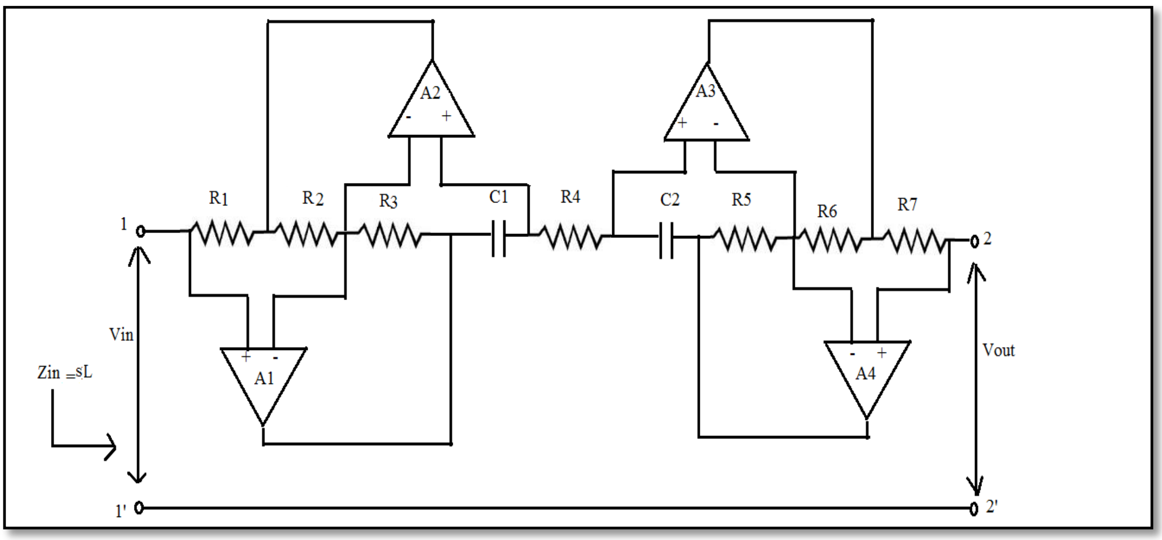


Figure 4.4 Floating Inductor realization using two GIC circuits

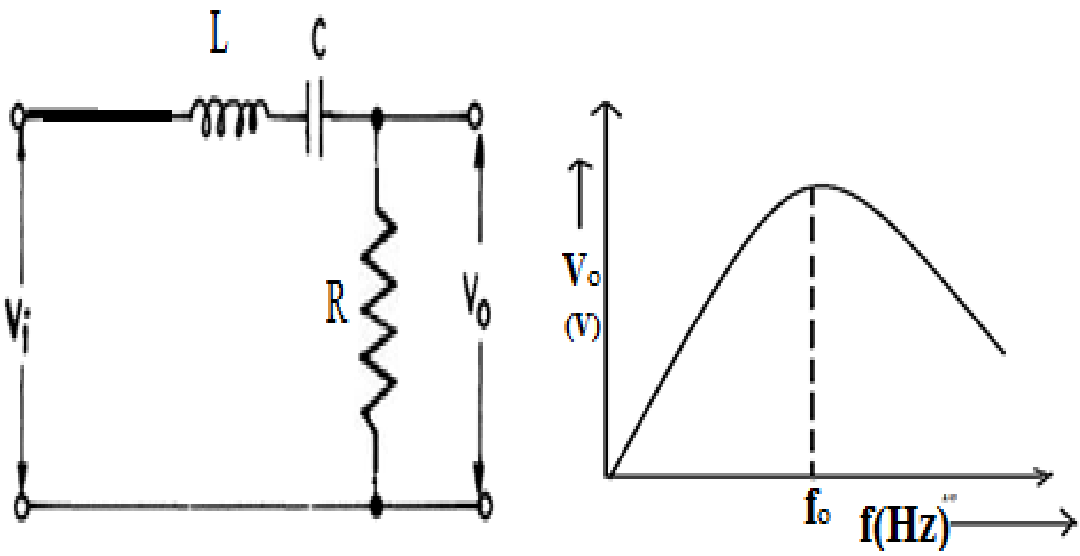
The equivalent impedance as seen at the input node is given below:

$$Z_{in} = L = R^2C \quad (4.2)$$

With all resistances are of same value and all capacitance are also equal i.e.

R1 = R2 = R3 = R4 = R4 = R6 = R7 = R ;and C1 = C2 = C.

The values of R and C are 4.7 KΩ and 6nF respectively for simulating 17 .2 H of inductance at 400 Hz and for simulating 9.1H of inductance at 1 KHz the values of R and C are 4.7K and 3nF respectively. We verified these inductor values using RLC series resonance circuit as shown in fig 4.5 with 'L' as simulated Floating inductor and the values of R and C are selected appropriately according to the frequency and inductance required.



(a) (b)

Figure 4.5 RLC series resonance circuit

Using the formula given below we can calculate the simulated inductance:

$$f_0 = \frac{1}{2\pi\sqrt{LC}}; \quad L = \frac{1}{4\pi^2 {f_0}^2 C} \tag{4.3}$$

4.2.2 Simulation of electrical prototype model*: *Model 1

Fig 4.6 shows the simulink model of Model 1 ie electrical prototype of PAC system. In this simulation model two inputs are used i.e. unit step as DC signal and a step input with 0.2pu sinusoidal offset at 4 Hz frequency and a switch is used to switch the supply from AC to DC source. As charge is analogous to displacement and output voltage is to contact force hence charge and output voltage across C_{av} and charge is measured by integrating the difference of the current flowing through C_h and C_{av}.

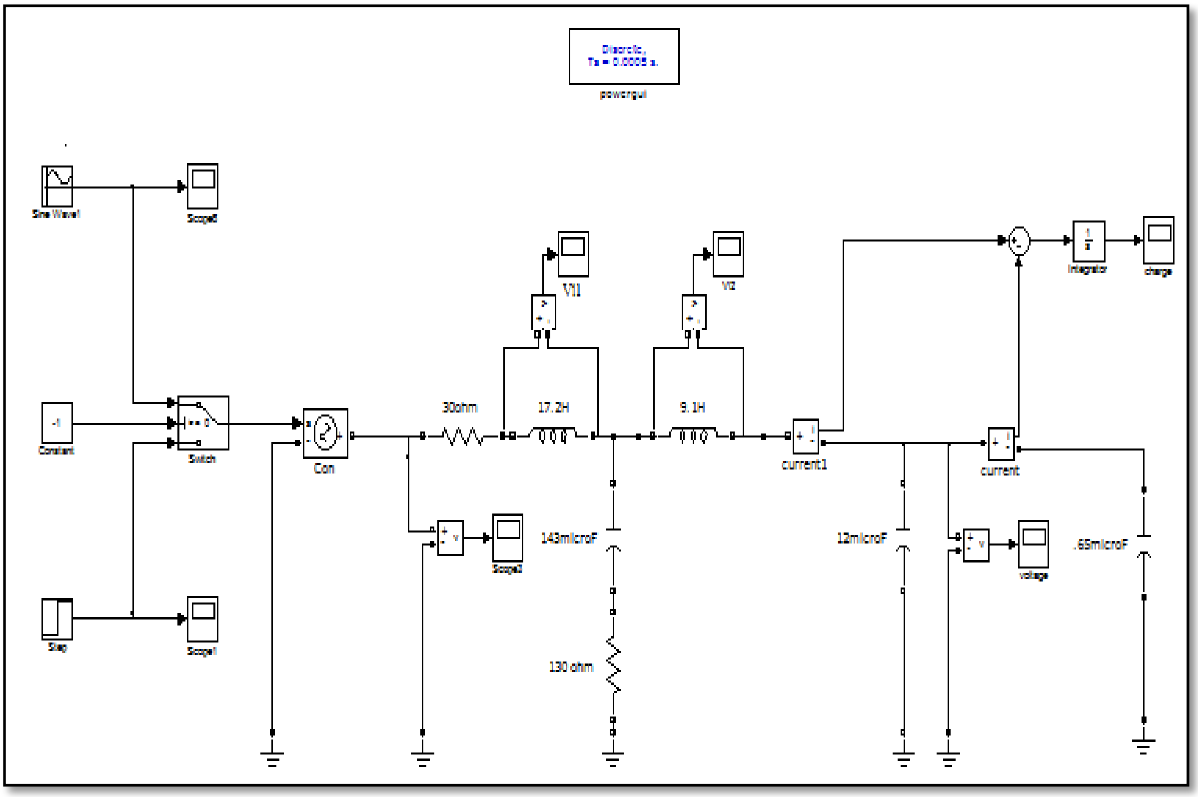


Figure 4.6 Simulink model of Model 1

The simulink response of displacement of catenary for mechanical model and the corresponding charge for analogous electrical model is studied under two input conditions i) when pantograph is fed with 1 p.u. step input representing constant contact force and ii) when pantograph is fed with 1 p.u. step input, with sinusoidal offset of 0.2 p.u. of frequency 5Hz added to it representing the oscillations in the contact force due to the translational movement of electric train. The electrical analogous model responses with both inputs are as shown in fig.4.8 (a), fig.4.9 (a), fig.4.10 (a), and fig 4.11(a) respectively.

4.2.3 Simulation of Mechanical Model: Model 2

Model 2 i.e. Mechanical model is simulated with two inputs ie step input and step input with 0.2 pu sinusoidal offset at 5Hz as shown in fig 4.7.The responses are shown in fig.4.8(b), fig.4.9(b), fig.4.10(b), and fig.4.11(b) respectively.

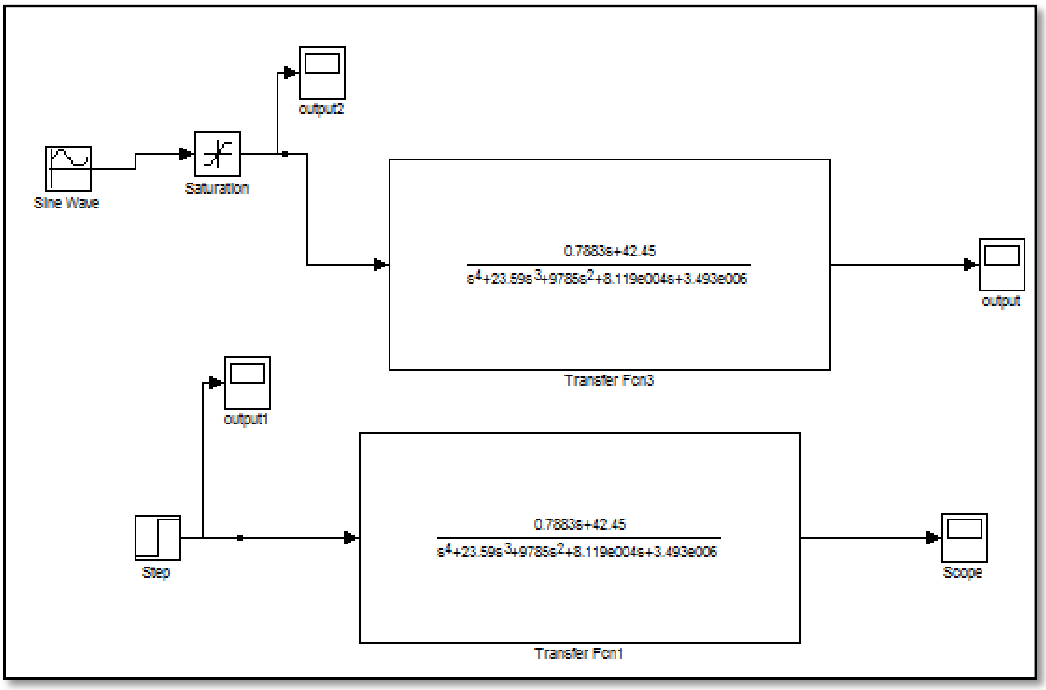
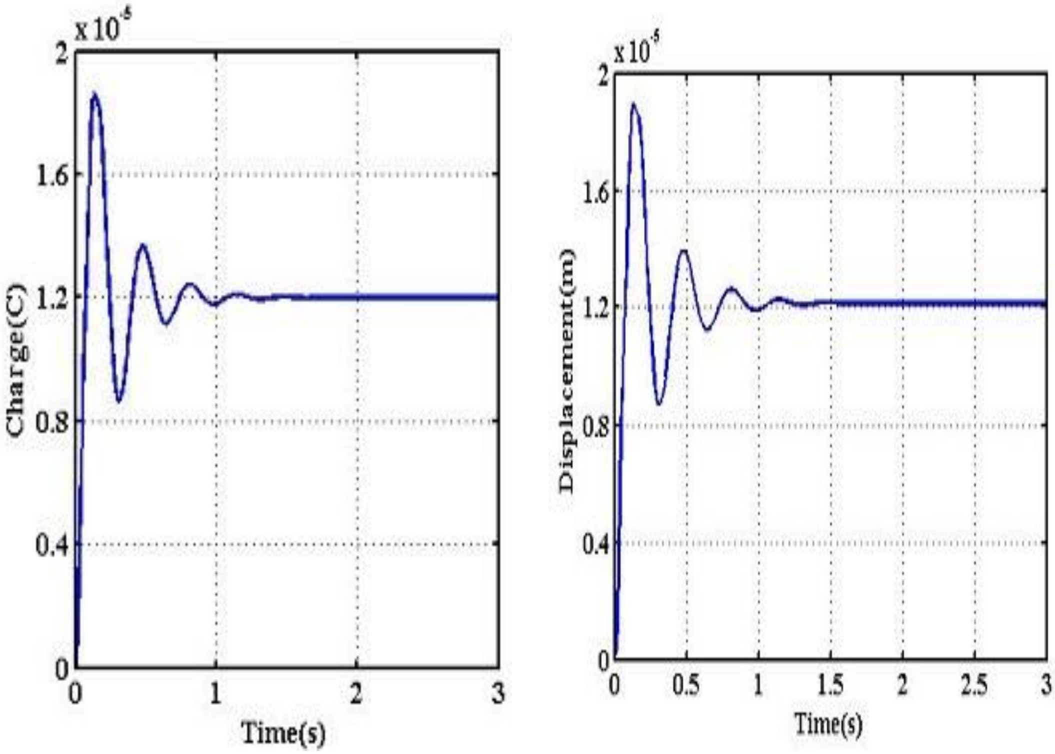
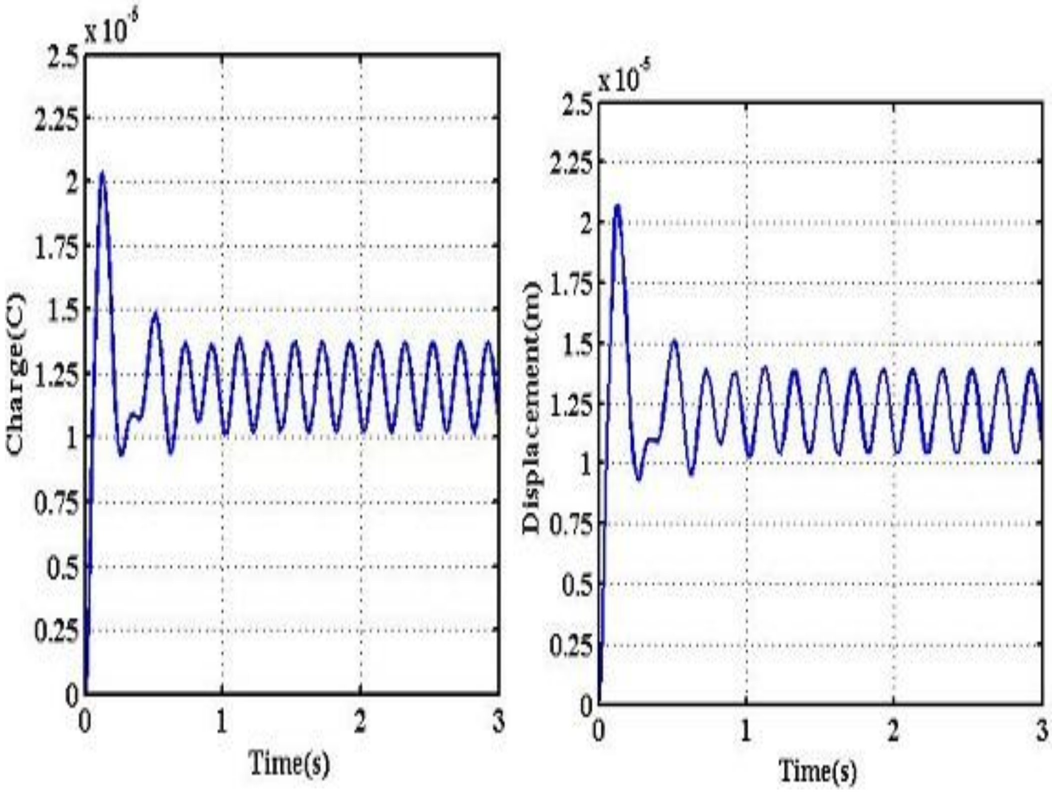


Figure4.7 Simulink model of Model 2 with two different inputs



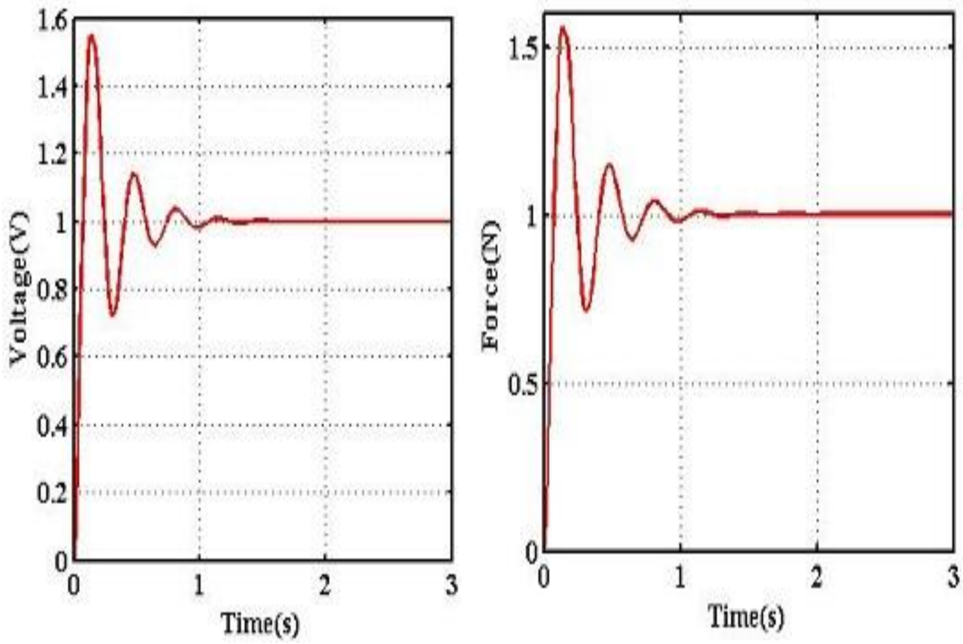
(a) Charge for electrical model (b) Displacement for mechanical model

Figure 4.8 Response for 1 p.u. step input



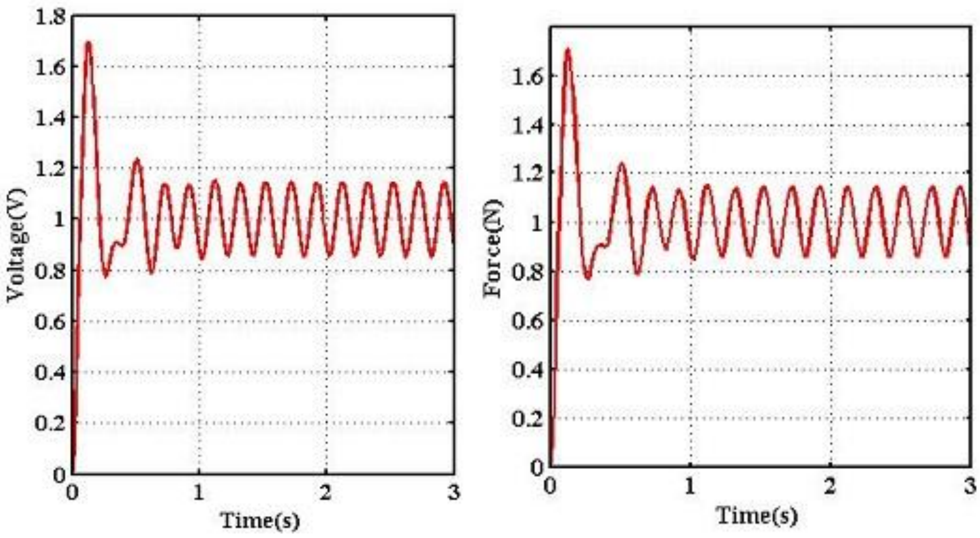
(a) Charge for electrical model (b) Displacement for mechanical model

Figure 4.9 Response for 1 p.u. step input with sinusoidal offset of 0.2p.u. at 5Hz



(a) Voltage for electrical model (b) Contact Force for mechanical model

Figure 4.10 Response for 1 p.u.step input



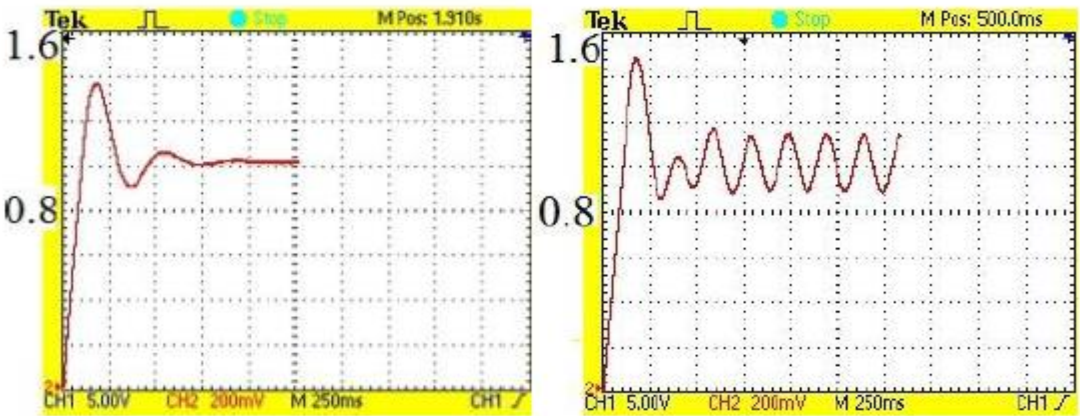
(a) Voltage for electrical model (b) Contact Force for mechanical model

Figure 4.11 Response for 1 p.u. step input with sinusoidal offset of 0.2p.u. at 5Hz

Comparison of all the responses of the model 1 and model 2 is shown in fig 4.8, 4.9, 4.10, and 4.11. Here we can infer that all the responses of electrical analogous model is same as that of mechanical model thus the electrical analogous model can be verified.

4.2.4 Hardware results: Model 3

The hardware setup is used for getting response of the electrical prototype of PAC system. The response of this system with two different input signals is captured on CRO as shown in fig 4.12.



(a) Step input response (b) Step input response with 0.2 p.u. offset at

Figure 4.12 Response of the Electrical prototype

As stated before that the displacement of the catenary is proportional to charge, but it is difficult to take the waveform of charge on CRO, therefore, voltage across capacitor is taken which will represent charge when multiplied by C_s-C_{av}. The simulink response of voltage, $V_o(s)$, of electrical model of PAC system is shown in Fig. 4.12(a). The simulink response for corresponding force for the mechanical model is shown in Fig. 4.12(b).

TABLE 4.1

COMPARISON OF ELECTRICAL PROTOTYPE RESULTS WITH ELECTRICAL ANALOGOUS MODEL AND MECHANICAL SIMULINK MODEL

Para-meters	Step Input (1 p.u.)			Step input (1p.u.) with sinusoidal offset of 0.2 p.u. added to it		
	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
t_s(s)	1.12	1.12	1	1	1	1
M_p(%)	55.9	55.9	40	55.7	55.7	50

The results for three models namely Model 1, Model 2, and Model 3are compared in Table 4.1. It is observed that for both the inputs, the settling time and the steady state values are same for all the models. However, for the peak overshoot, results for model 1 and model 2 are similar while the small deviation in the corresponding value of model 3 may be due to slight variation of values for capacitor and inductor used in actual hardware circuit from their synthesized values and due to the tolerance of the components and experimental errors.

4.3 Conclusion

Here electrical prototype of PAC system is described and simulated successfully. The results of the hardware are then verified with respect to both simulink models namely Electrical Analogous simulink, and Mechanical simulink.

CHAPTER V

ACTIVE CONTROLLERS FOR PAC SYSTEM

CHAPTER V

ACTIVE CONTROLLERS FOR PAC SYSTEM

Introduction

This chapter presents the designing of active controllers for PAC system. Firstly a control algorithm is presented for the basic idea of control of PAC system. Further all the controllers namely PID, Fuzzy Logic, Fuzzy PID and ANFIS designed for controlling are explained in detail.

5.2 Control Algorithms

The preceding work in chapter III is further used to facilitate the construction of a complete model for controlling of the elementary PAC system. The basic feedback system model as shown in fig 5.1 is used as a basis for expansion to the more detailed model shown in fig 5.2, which has featured in similar form in other conventional control systems work.

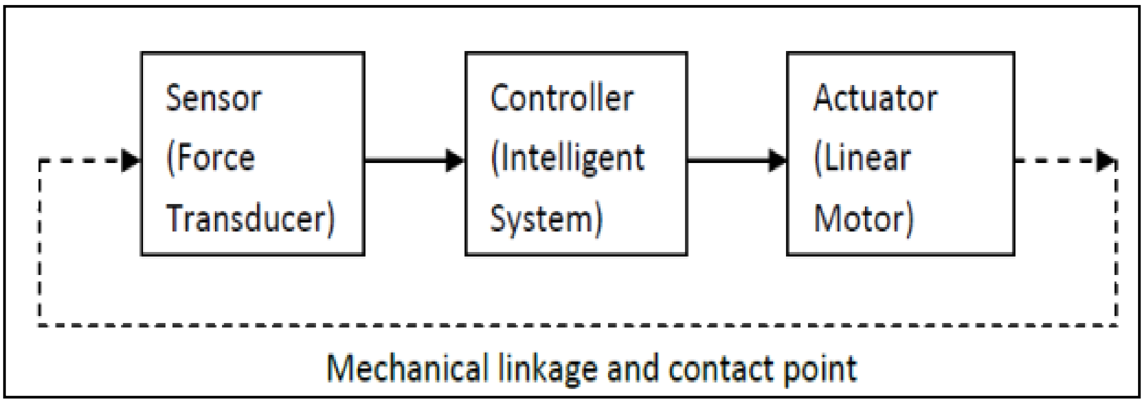


Figure 5.1 Concept for PAC active control

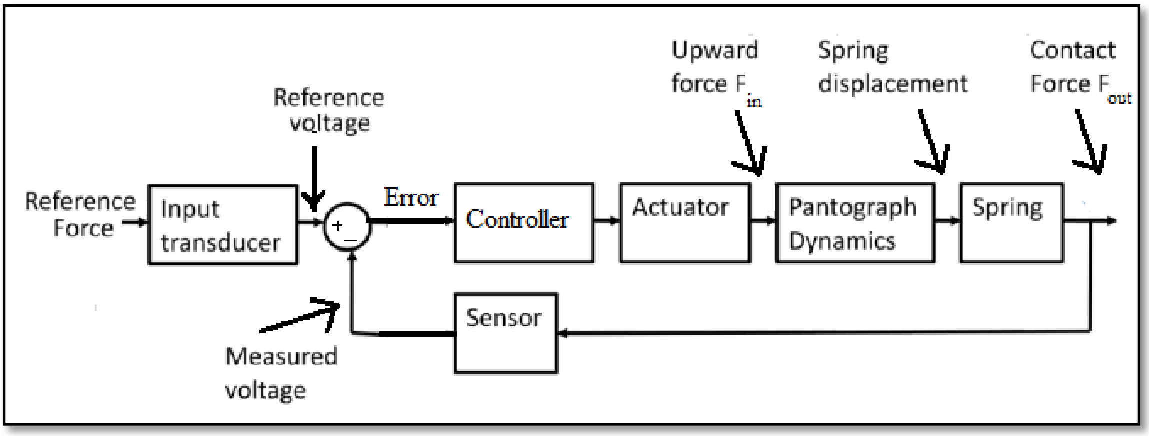


Figure 5.2 Block diagram of closed loop Active PAC control system

The system input is the value of the desired reference contact force. The difference between the reference value and the output value of the system is the error value and fuzzy logic control is to minimize the error value and its derivative.

The frame actuated design is chosen over head actuated design as in head actuated design, the actuator is required to move with the pantograph head, which will increase the overall weight of the system and thus slows down its performance. Actuator applies the necessary uplift force to the pantograph in order to move upward.

5.3 Active Controllers for PAC System

Here in this study, firstly fuzzy logic controllers of different membership functions comprising of triangular, gauss, gbell and sigmoid mfs, are designed and compared with conventional PID controller. Main emphasis is kept on the peak overshoot and settling time of the contact force. So far in the literature, no comparison is available for the different membership function for the fuzzy logic controllers for the PAC system.

Further intelligent controllers namely Fuzzy Logic Controller, Fuzzy PID and Adaptive Neuro Fuzzy Inference System for PAC system are designed at two speed i.e. 150km/hr and 200km/hr and then simulated using MATLAB-Simulink. All controllers are then compared with open loop controller and suitable results are obtained.

5.3.1 PID Control

PID controllers are the most commonly used controllers in control loops due to their simplicity and ease of design. PID controllers decreases the settling time and improves the steady state response. The PID controller consists of three separate control actions: the proportional, derivative and integral as shown in fig 5.3. The weighted sum of these three actions is used to adjust the force through an actuator. The transfer function of the PID controller is given by

$$K_p e(t) + K_i \int_0^t e(t)\,dt + K_d \frac{de(t)}{dt} \qquad (5.1)$$

where e(t) is error wrt reference input signal and K_p, K_i and K_d are the three control parameters i.e. proportional constant, integral constant and constant of derivative respectively. The proportional constant is responsible for following the desired set-point, while the integral and derivative part account for the accumulation of past errors and the rate of change of error in the process respectively. The weighted sum of all the three actions is used by the PID controller. By tuning these three control parameters in the PID controller algorithm, the controller can provide control action designed for specific process requirements.

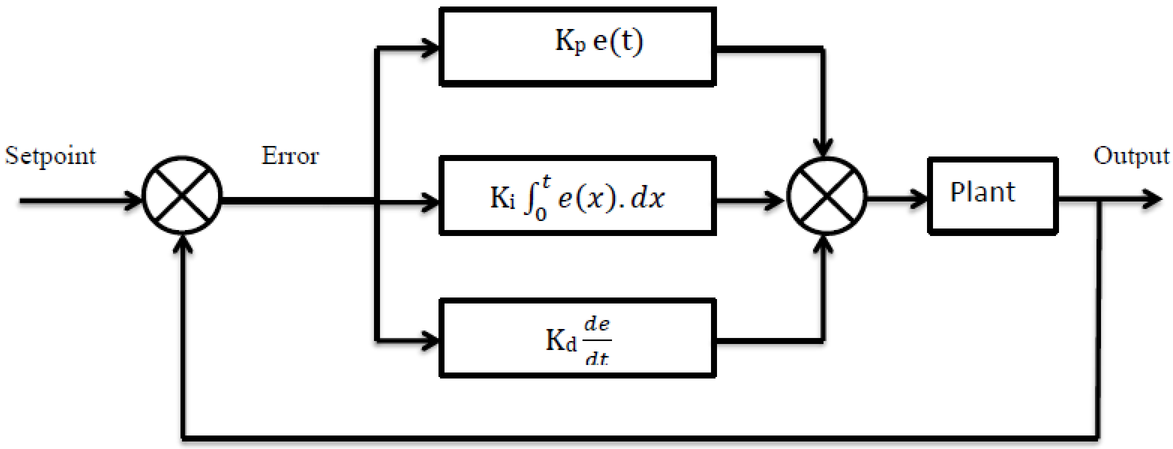


Figure 5.3 Block diagram of a PID controller in a feedback loop

5.3.2 Fuzzy Logic Control

Fuzzy logic is a mathematical tool or the analysis and management of uncertainties in a given system. It is a nonlinear adaptive control method based on artificial intelligence. To take into account, the ambiguous and uncertain nature of vibrations in contact force, fuzzy logic control is applied to minimize these vibrations. The principal components of a fuzzy logic system are:

(i) fuzzifier, (ii) an inference engine (a knowledge base comprising of data base and rules base) and (iii) defuzzifier.

Fuzzification is the process of transformation of uncertain crisp parametric value into corresponding fuzzy set values. Before the parameters are fuzzified, however, they should be first normalized to the range of universe of discourse and expressed in terms of membership function. The membership function is a graphical representation of the magnitude of participation of each input. It associates a weight with each of the input that is processed, defining functional overlap between inputs and ultimately determining an output response. The rules use the input membership values as a weighting factor to determine their influence on the fuzzy output sets of the output conclusion. Once the functions are inferred, scaled and combined, they are de-fuzzified into a crisp output, which is then used to compute the final output. Fig. 5.4 shows the block diagram for fuzzification.

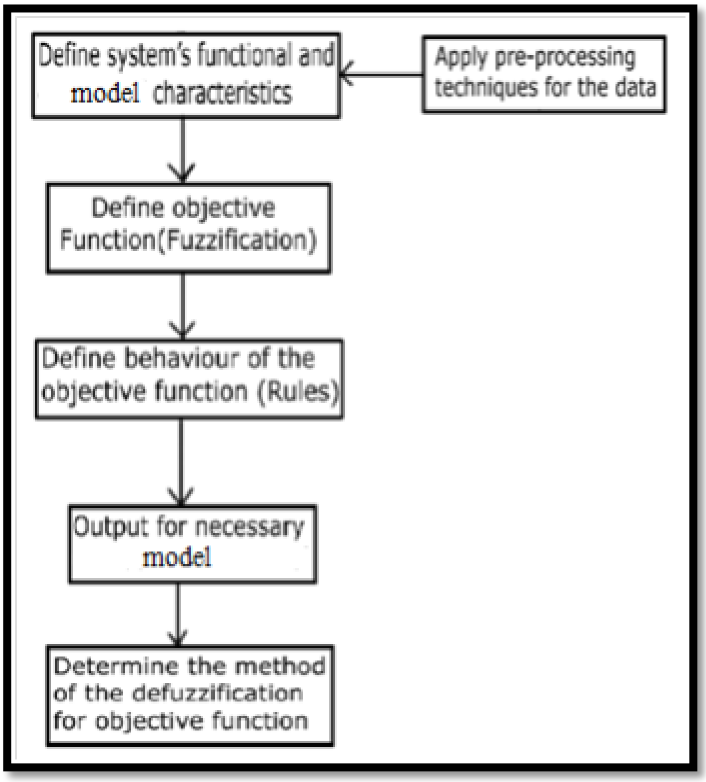


Figure 5.4 Block diagram for fuzzification

FLC is recently becoming popular with the systems requiring of robust control i.e. where load and process parameters vary [48]. Zhao and Bose [49] imply that triangular mfs are easy to implement and the response of trapezoidal also follows triangular response closely.

They performed the vector control of induction motor with different FLC mfs but stated that it can be generalized to other control systems also.

For the PAC system, two different controllers using fuzzy logic control are designed with single input and two inputs where error is single input and error and change in error are two inputs respectively. These controllers are designed using triangular, gbell, gaussian and sigmoid membership functions as shown in fig 5.5 and the rule base is given in fig 5.6. All these membership functions are continuous in nature. Since all information contained in a fuzzy set is described by its membership function, it is useful to describe various special features of these functions.

A triangular MF is specified by three parameters {a, b, c} as given by (5.2),

$$triangle\,(x;a,b,c) = \begin{cases} 0, & x \le a \\ \frac{x-a}{x-b}, & a \le x \le b, \\ \frac{c-x}{c-b}, & b \le x \le c, \\ 0, & c \le x. \end{cases} \qquad (5.2)$$

where {a, b, c} (with a < b < c) determine the x coordinates of the three corners of the underlying triangular MF.

A Gaussian MF is specified by (5.3),

$$gauss(x;c,\sigma) = e^{-\frac{1}{2}[\frac{x-c}{\sigma}]^2} \qquad (5.3)$$

where c is the centre of mf and σ determines the MFs width.

A Generalized Bell MF is specified by three parameters {a, b, c} as given by (5.4),

$$gbell(x;a,b,c) = \frac{1}{1+\left|\frac{x-c}{a}\right|^{2b}} \qquad (5.4)$$

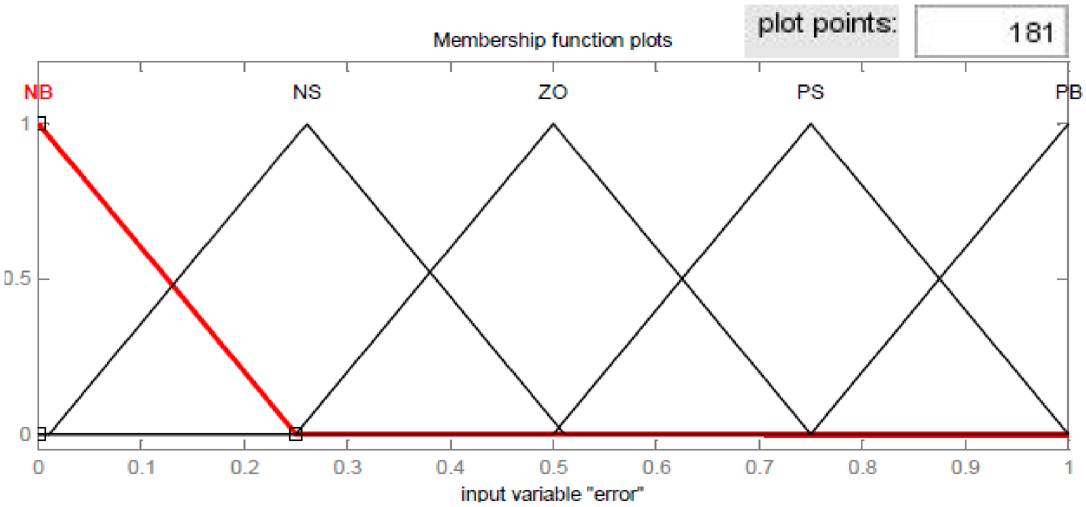
where b is usually positive. If b is negative, the shape of this MF becomes an upside-down bell.

A sigmoid MF is defined by (5.5),

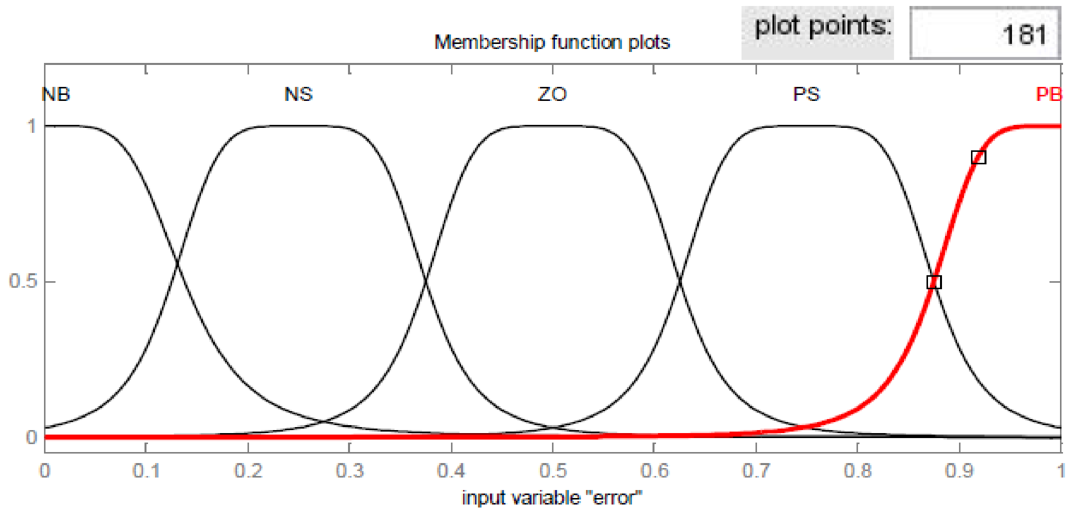
$$sigm(x;a,c) = \frac{1}{1+exp[-a(x-c)]} \qquad (5.5)$$

where *a* controls the slope at the crossover point, x=c.

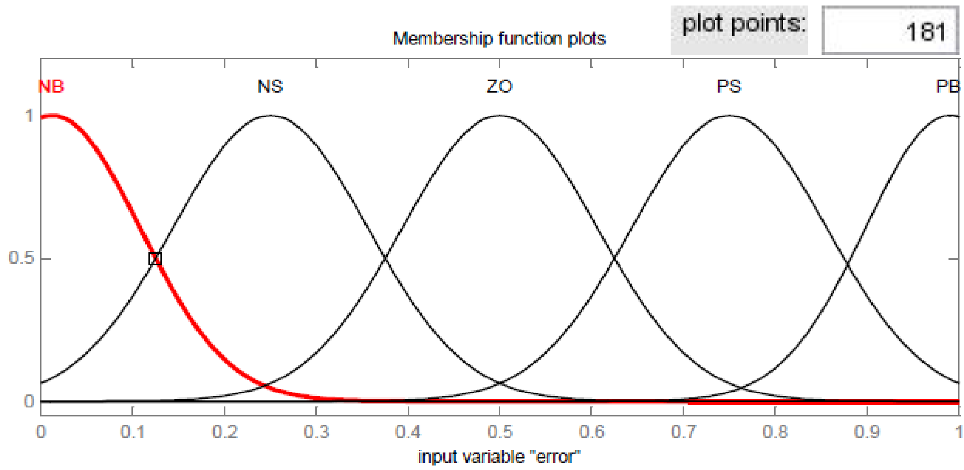
The triangular fuzzy membership shape is commonly employed in control applications due to primarily low computational costs of creating and integrating triangular fuzzy sets. However, they are less robust. The sigmoid function and g-bell-shaped fuzzy functions are better in robustness since their center value is not a single point [50]. The gaussian MF is quite popular in the fuzzy logic literature, as they are the basis for the connection between fuzzy systems and radial basis function (RBF) neural networks.



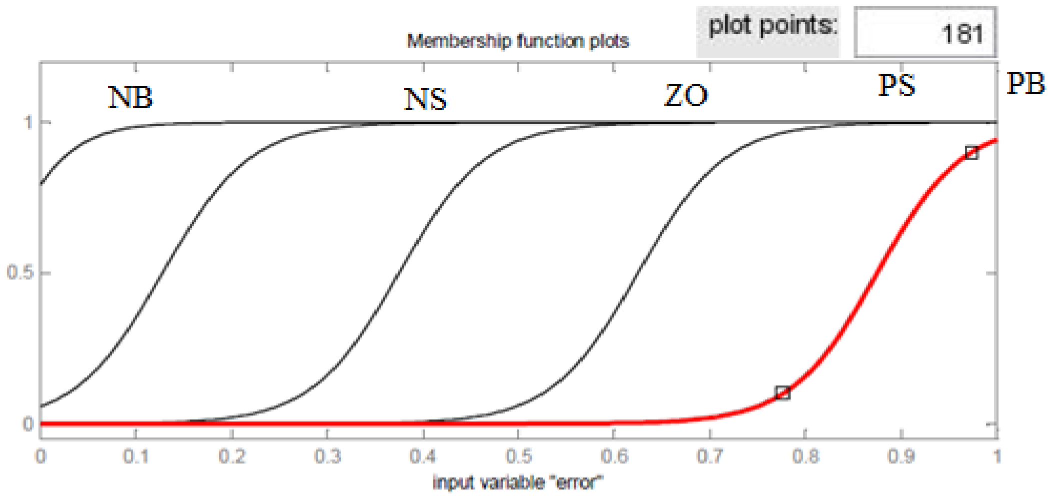
(a) Triangular mfs



(b) Gbell mfs



(c) Gauss mfs



(d) Sigmoid mfs

Figure 5.5 Input and Output FLC mfs.

$\dot{\Delta e}$ \ Δe	NB	NS	ZO	PS	PB
NB	NB	NB	NB	NS	ZO
NS	NB	NS	NS	ZO	NS
ZO	NB	NS	ZO	PS	PB
PS	NS	ZO	PS	PS	PB
PB	ZO	PS	PB	PB	PB

Figure 5.6 Rule base for all FLCs

The best from all the mfs is then used for comparison with all other controllers and open loop system. One of the FLC namely good2ipgbell using gbell mf is shown in Fig 5.7.

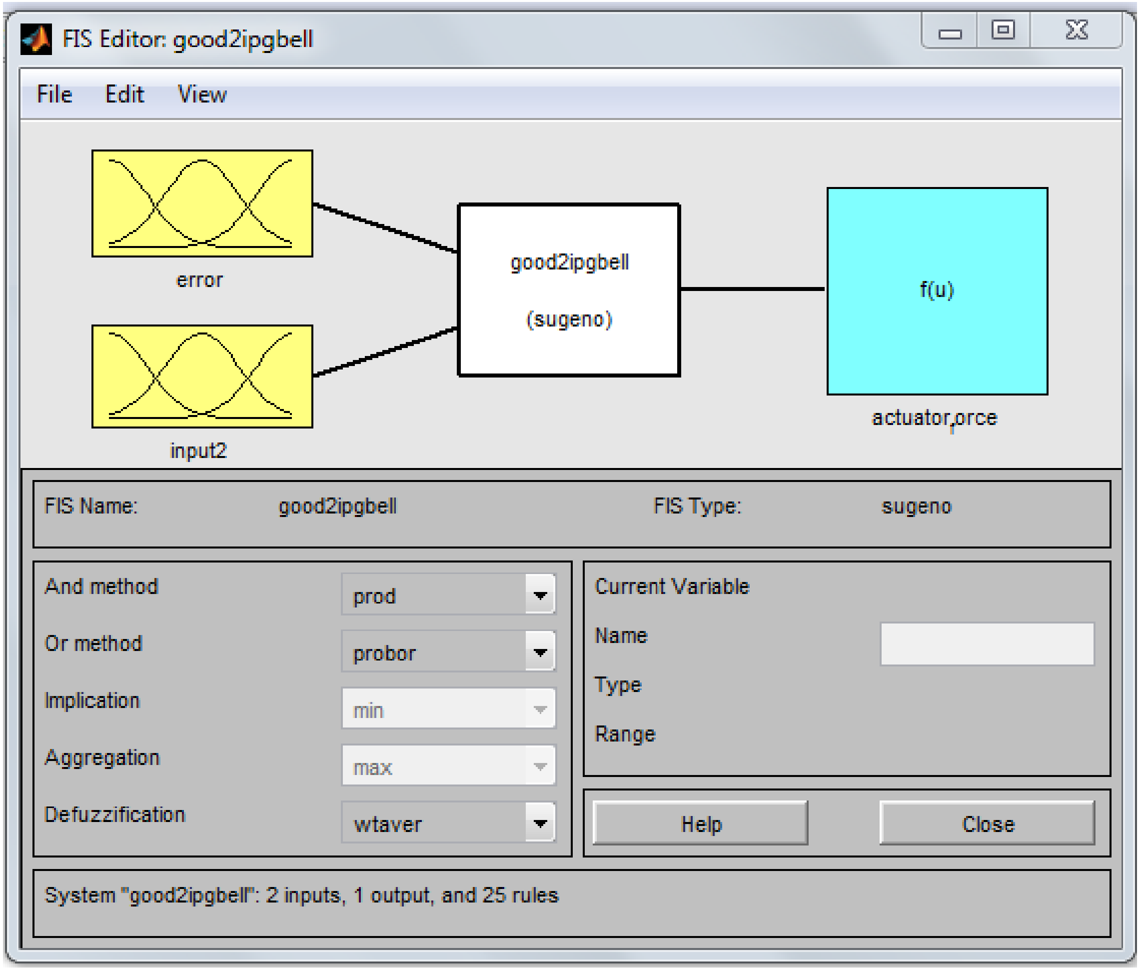


Figure 5.7 Gbell Fuzzy Logic Controller

5.3.3 Adaptive Neuro Fuzzy Inference System

Adaptive Neuro-Fuzzy Inference System combines the two theories namely fuzzy and neural to achieve better control on complicated objectives. ANFIS is a new type of fuzzy inference structure that combines fuzzy logic (FL) with neural network (NN) suitably. It is an adaptive network that is equivalent to fuzzy inference system in the function. A combination of neural networks and fuzzy logic offers the possibility of solving the tuning problems and design difficulties of fuzzy logic [50]. Fuzzy systems depend upon 'knowledge acquisition' from an expert. It is a time consuming process as the membership functions has to be determined and their ranges are to be decided on the basis of data collected.

Researchers from many scientific disciplines are designing artificial neural networks to solve a variety of problems in pattern recognition, prediction, optimization, associative memory, and control. Inspired by biological neural networks, Artificial Neural Networks (ANNs) are massively parallel computing systems consisting of an extremely large number of simple processors with many interconnections.ANN models attempt to use some “organizational” principles believed to be used in the human brain.
ANFIS is an adaptive network of nodes and directional links associated with the learning rule - for example back propagation. It’s called adaptive because some, or all, of the nodes have parameters which affect the output of the node. These networks are learning a relationship between inputs and outputs. The ANFIS approach learns the rules and membership functions from data and further train the data to follow the output.

a. The structure of ANFIS

Assumed that the considered fuzzy inference system has two inputs: x, y, and a single-output z. for first-order Sugeno fuzzy model, ordinary fuzzy rule set with two fuzzy rules is as follows:

$$If\ x\ is\ A_1\ and\ y\ is\ B_1\quad THEN\ f_1 = p_1 x + q_1 y + r_1$$

$$If\ x\ is\ A_2\ and\ y\ is\ B_2\quad THEN\ f_2 = p_2 x + q_2 y + r_2$$

A combination of neural networks and fuzzy logic offers the possibility of solving the tuning problems and design difficulties of fuzzy logic.
The ANFIS structure that is equivalent to this model is indicated in fig 5.8

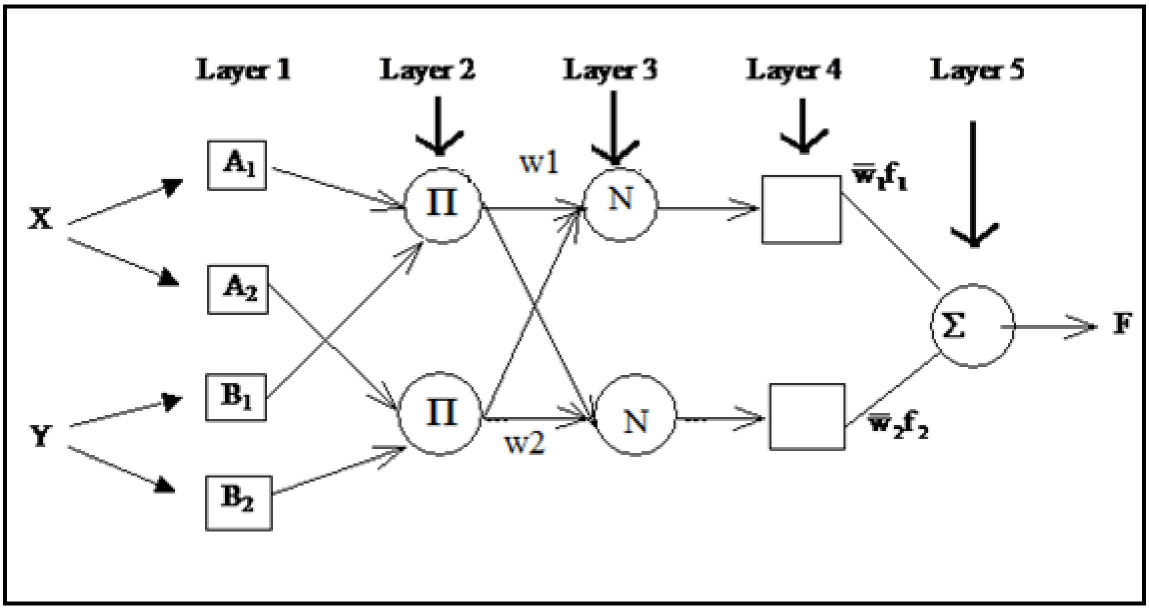


Figure 5.8 The ANFIS structure

b. ANFIS Steps

Following are the steps to follow to create ANFIS file as shown in fig 5.9:

Step1: Firstly a PID controller is tuned and when the results are satisfactory then its input error "e" and the derivative of error "ce" is saved in workspace and also the output of PID controller say "op" is also saved in workspace.

Step2: The two inputs e and ce and the output ie op gives the training data for ANFIS.

Step 3: Use anfisedit command to create ANFIS '.fis' file.

Step5: Load the training data from step 2 and generate .fis file using triangular mf.

Step5: Train the collected data upto particular no. of epochs

Step6: Plot it against training data and export the .fis file (as shown in fig 5.10) to workspace.

Step7: Use Fuzzy Logic Controller in place of PID controller from step 1 in the simulink model and run the model with .fis file saved in step 6 for ANFIS output.

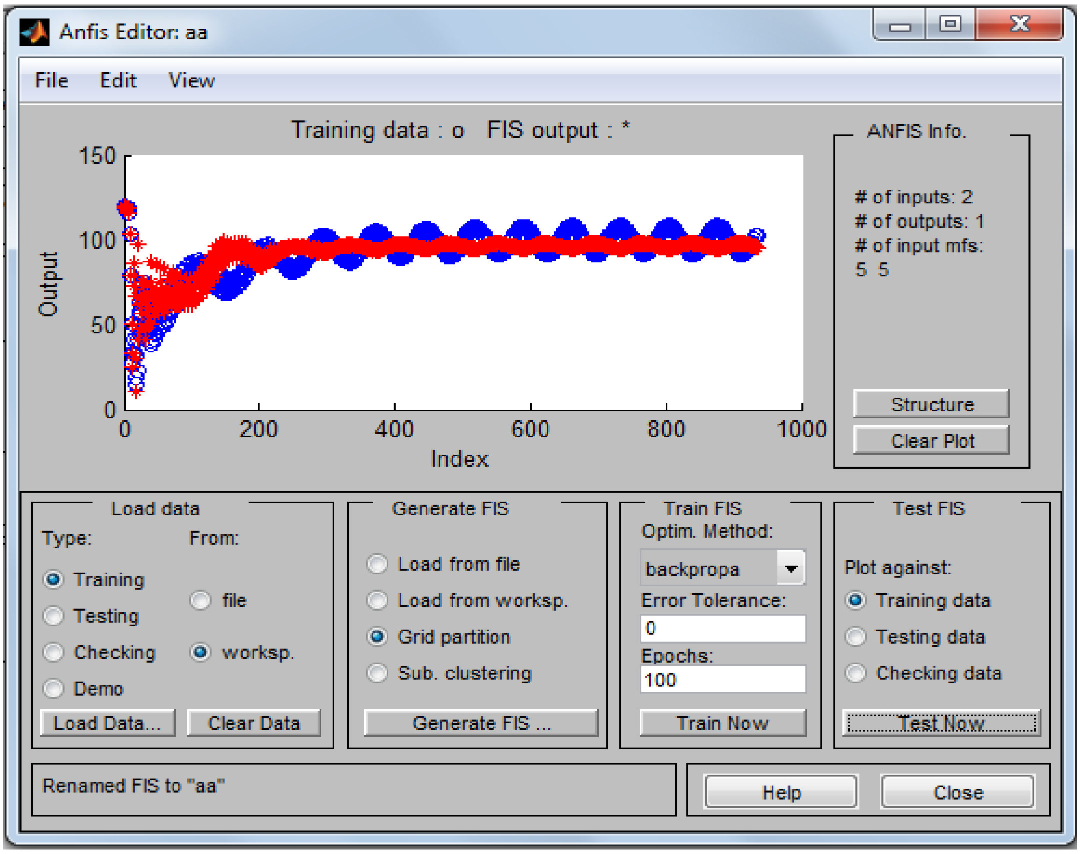


Figure 5.9 ANFIS Controller for PAC System

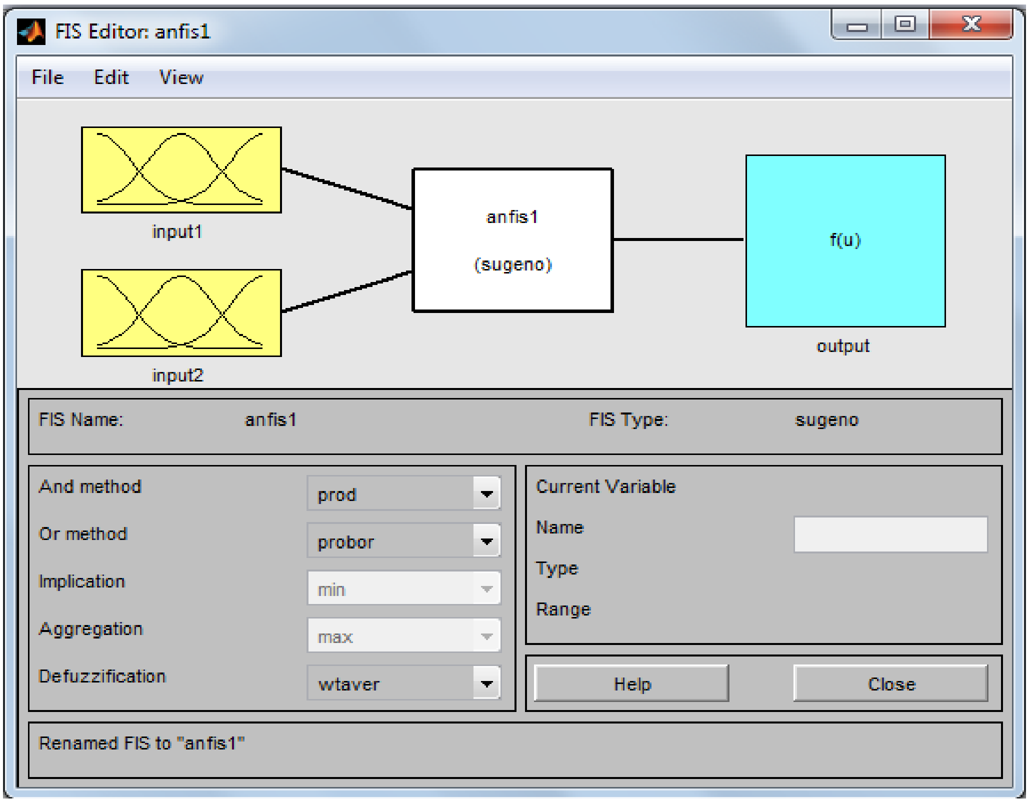


Figure 5.10 ANFIS .fis file

5.3.4 Fuzzy tuned PID

Fuzzy logic has been useful in recent years to formalize the ad-hoc approach of PID control. Mokrani and Rashid presented a Fuzzy PID control scheme for 3DOF model of PAC system considering 350km/hr speed [51]. A fuzzy PID controller uses the conventional PID controller as the foundation and takes the fuzzy reasoning and variable universe of discourse to regulate the PID parameters. The characteristics of a fuzzy system such as robustness and adaptability can be successfully incorporated into the controlling method for better tuning of PID parameters.

The term self-tuning refers to the characteristics of the controller to tune its controlling parameters on-line automatically so as to have the most suitable values of those parameters which result in optimization of the process output. Fuzzy self-tuning PID controller works on the control rules designed on the basis of theoretical and experience analysis. Therefore, it can tune the parameters Kp, Ki, and Kd by adjusting the other controlling parameters and factors on-line. This, in result makes the precision of overall control higher and hence gives a better performance than the conventional PID controller or a simple fuzzy PID controller without self-tuning ability.

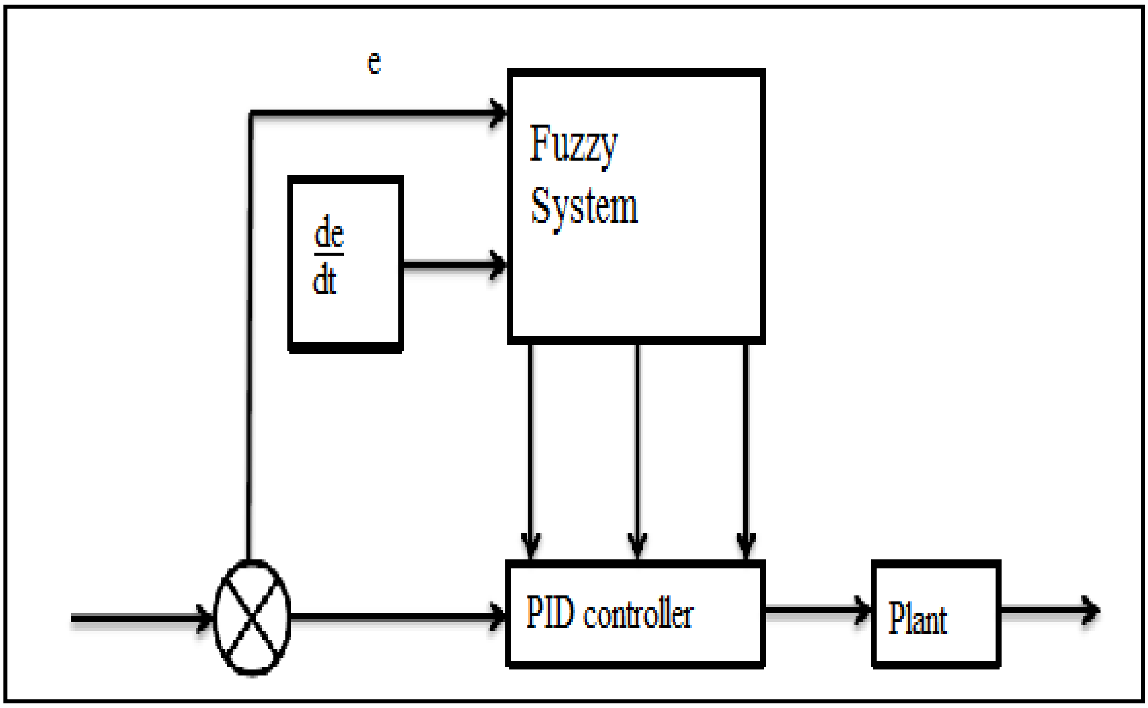
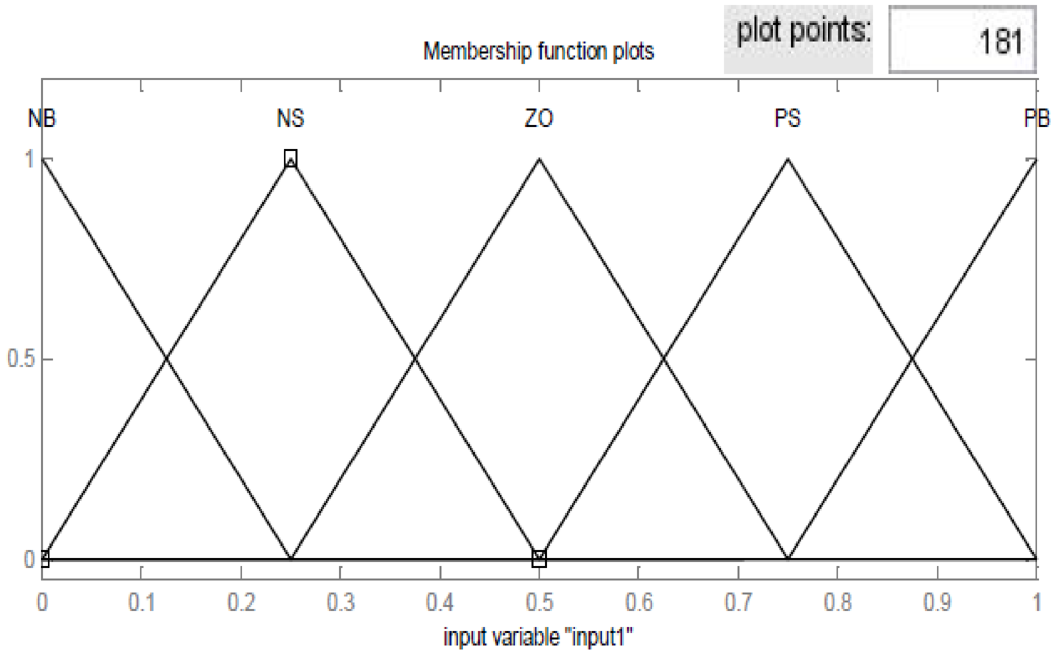
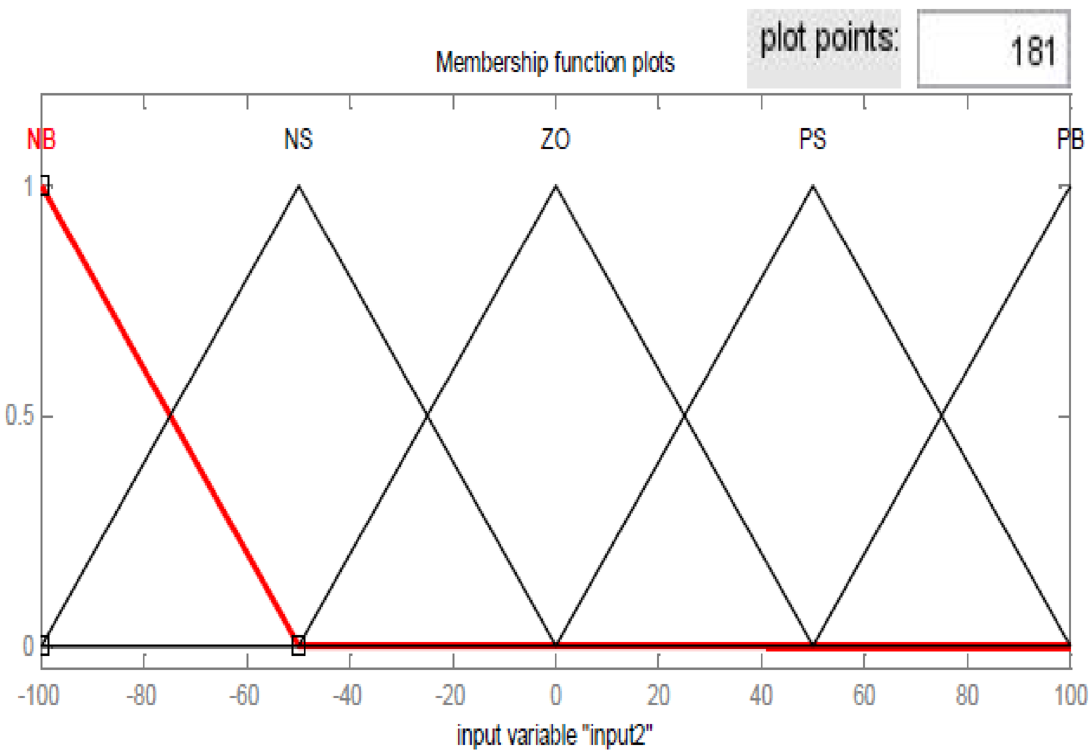


Figure 5.11 Block diagram of Fuzzy tuned PID

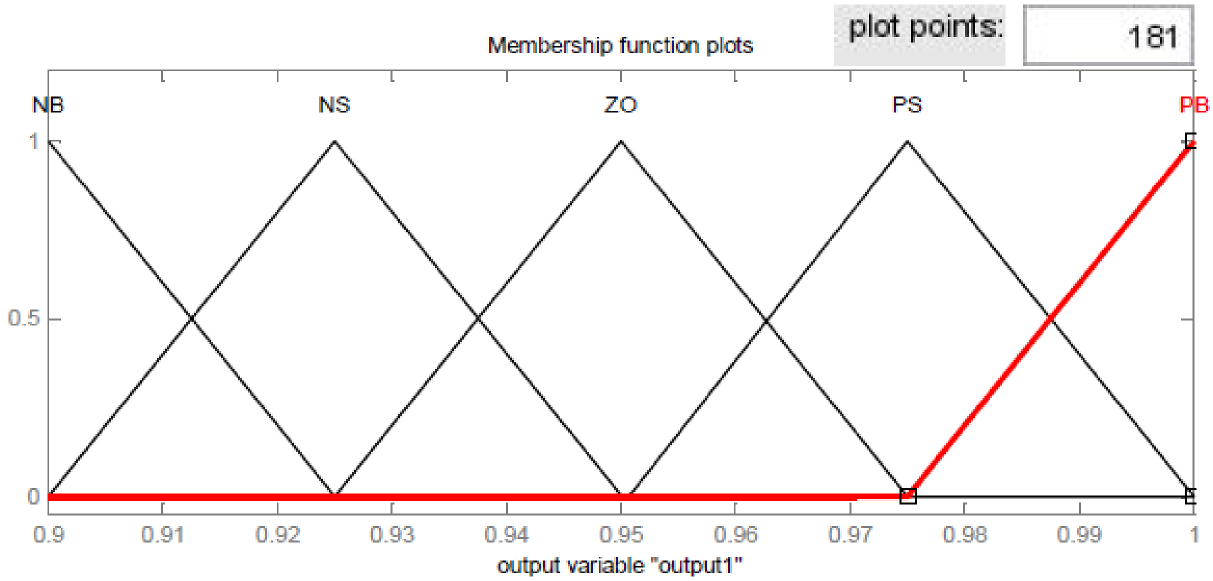
The Fuzzy tuned PID Fuzzy Logic Controllers are shown in fig 5.12-5.14 and the rule base is specified in fig 5.15. Here mamdani type proportionel, integrater and derivative FLCs are used.



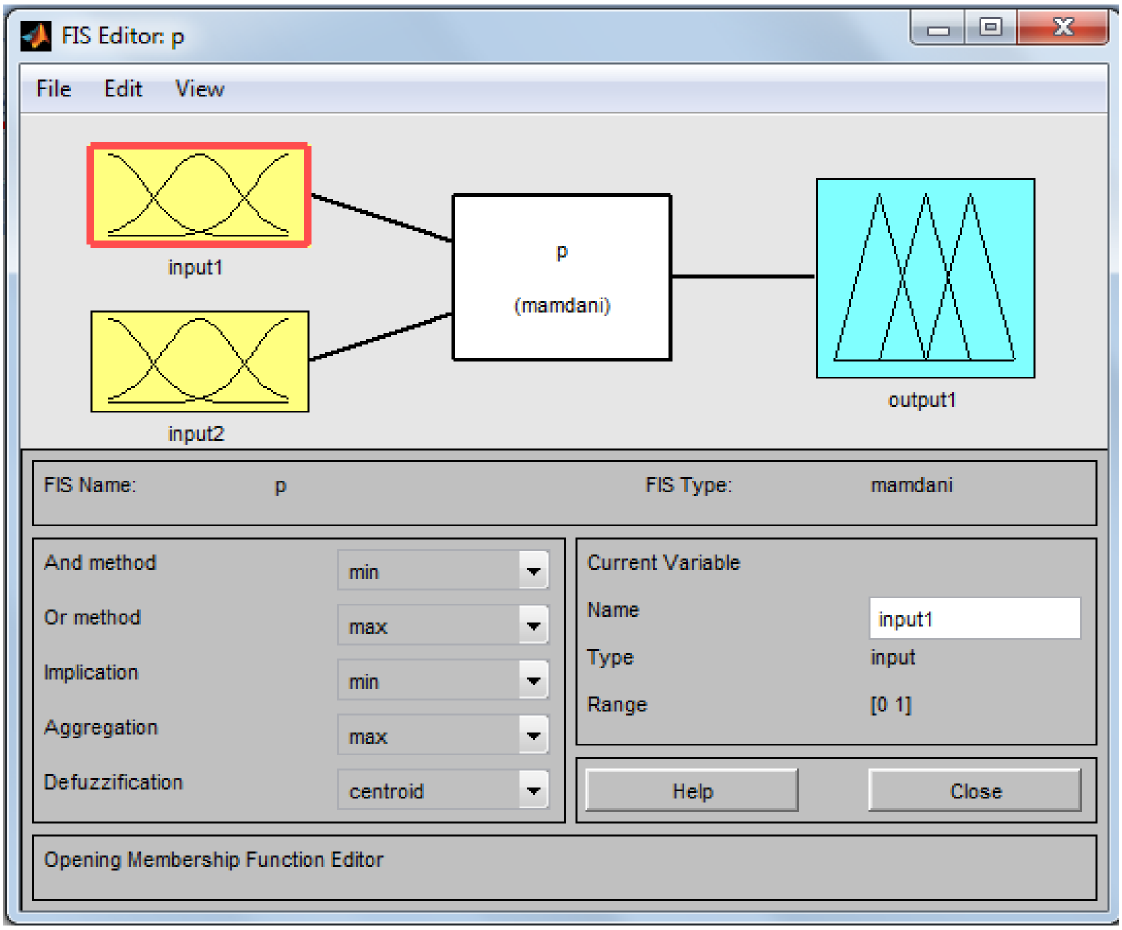
(a) Input 1 of Kp controller



(b) Input 2 of Kp controller

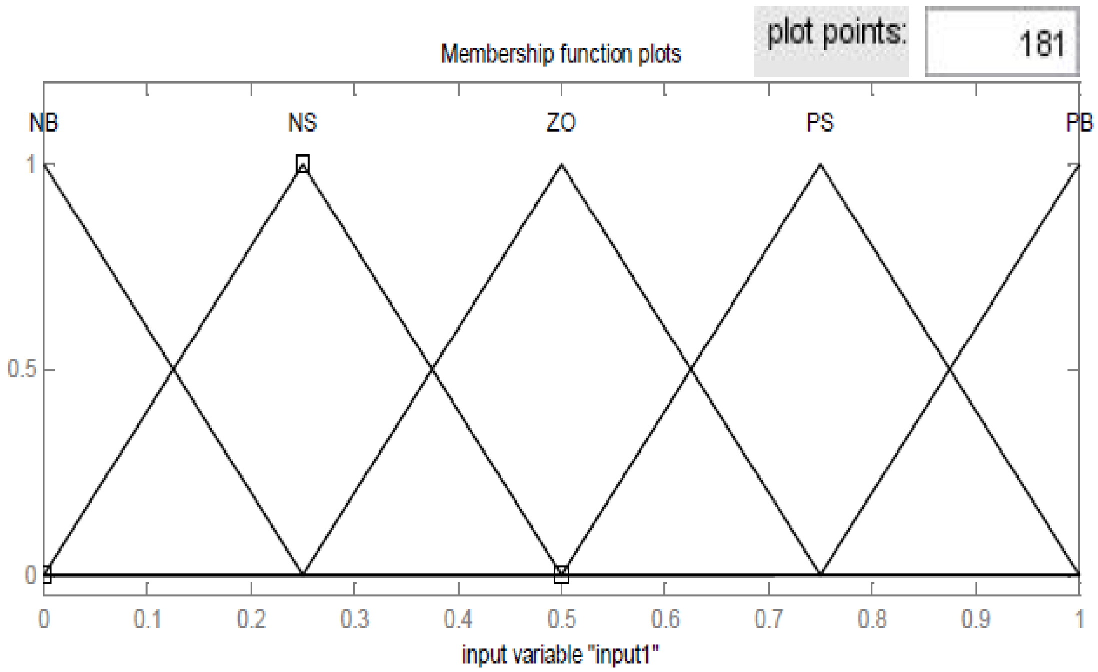


(b) Proportional Output membership functions

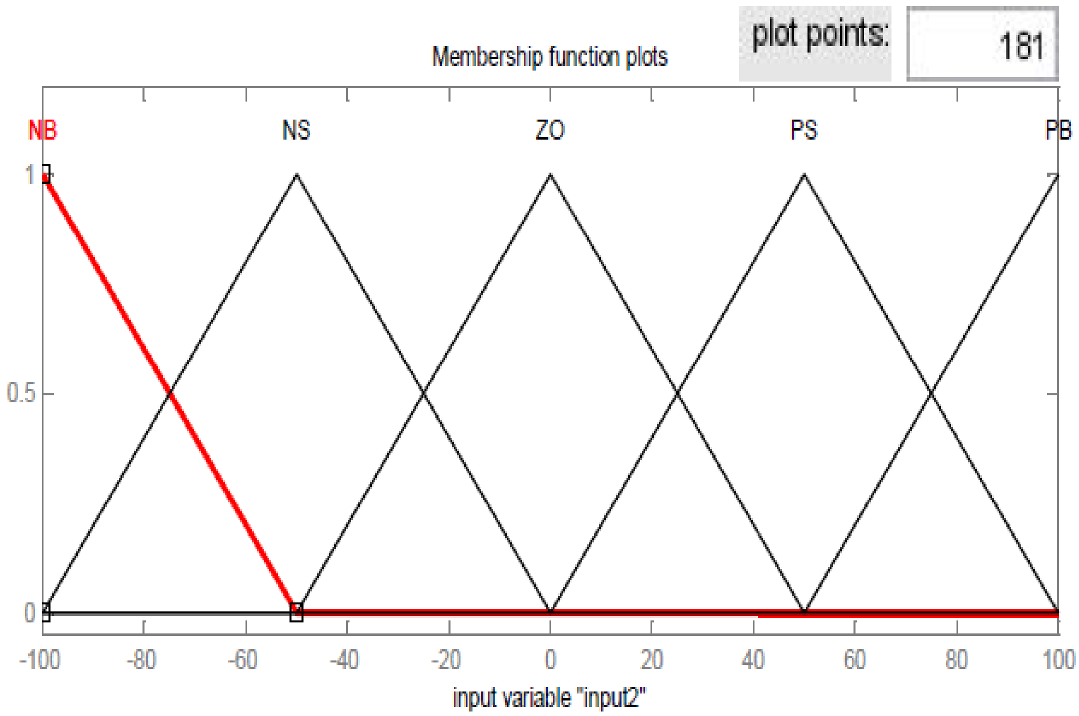


(d) Propotional FLC Kp

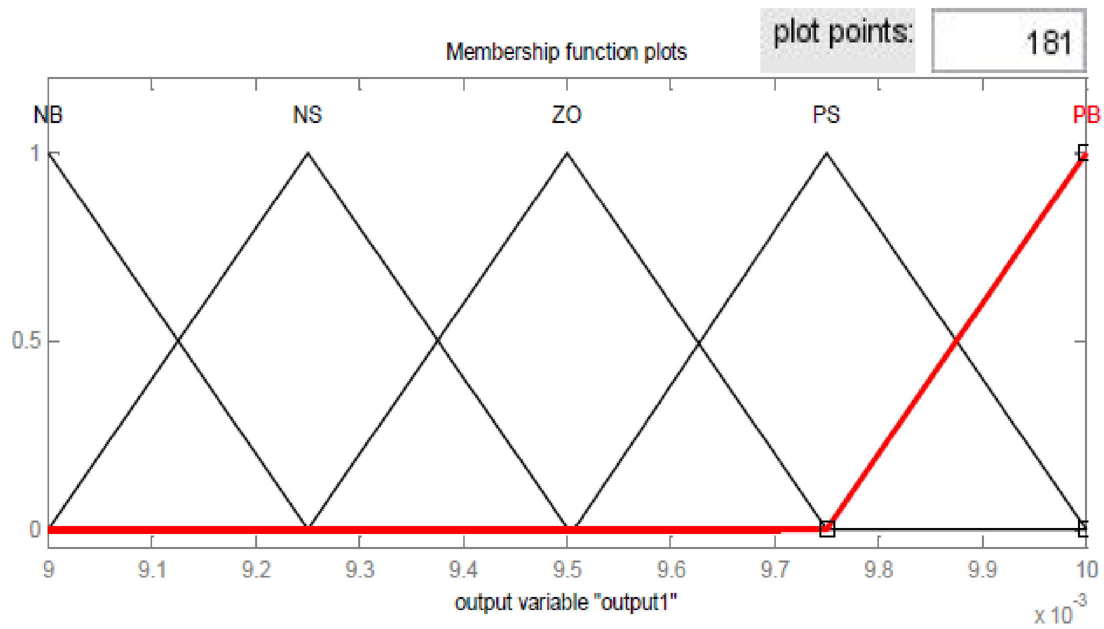
Figure 5.12 Fuzzy tuned Proportional Controller



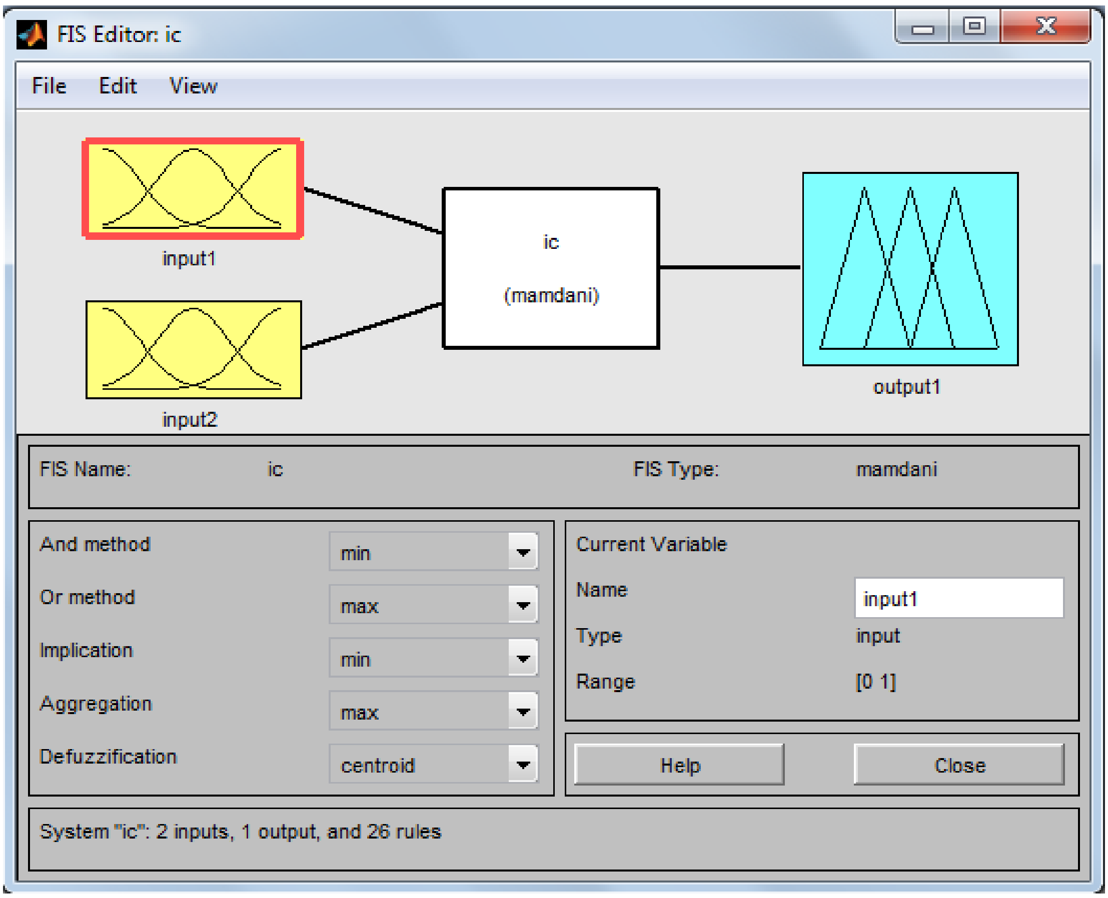
(a) Input 1 of Ki controller



(b) Input 2 of Ki controller

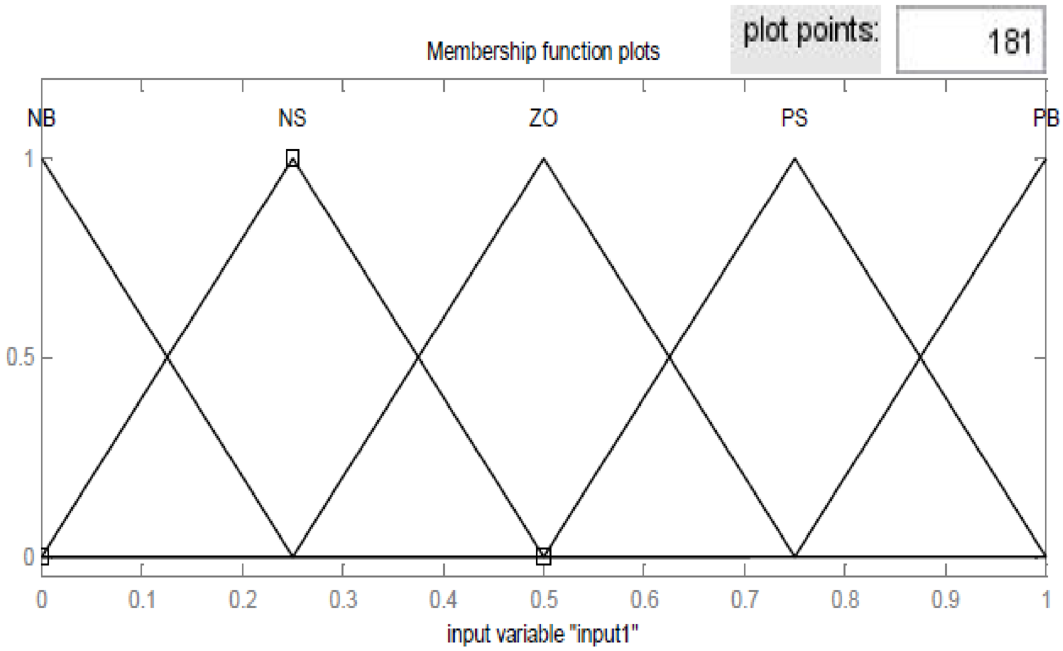


(c) Ki output Membership function

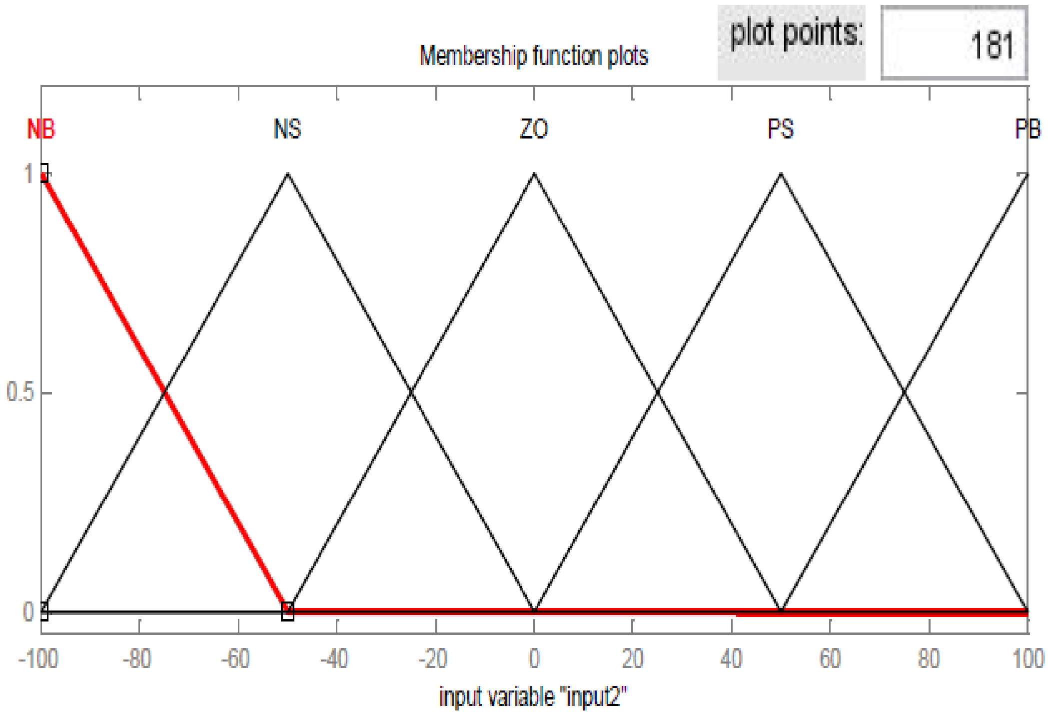


(d) Integral FLC Ki

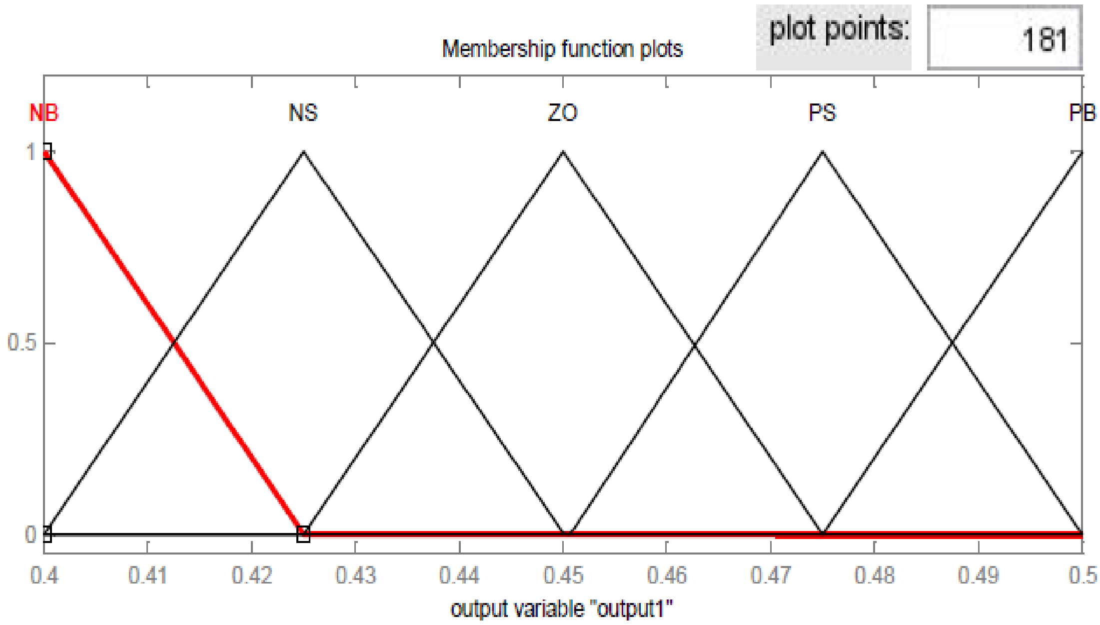
Figure 5.13 Fuzzy tuned Integral Controller



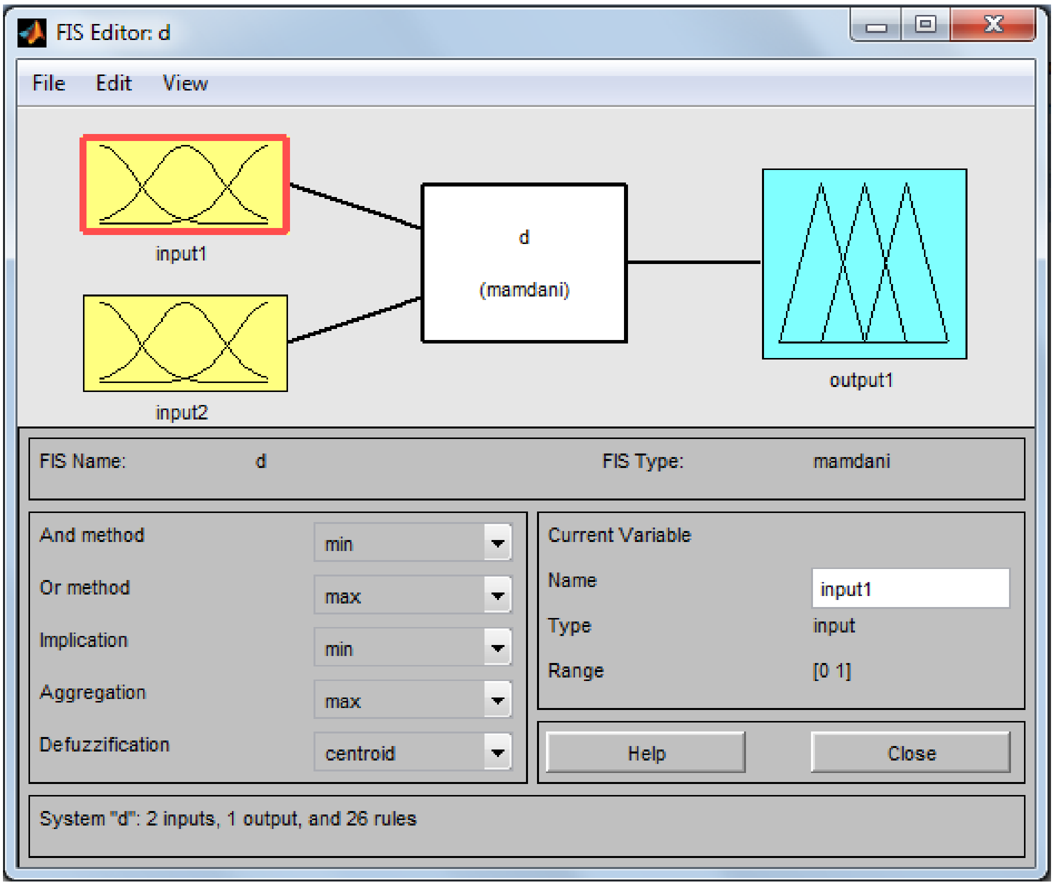
(a) Input 1 of Derivative controller



(b) Input 2 of Derivative controller



(c) Output of Derivative controller



(d) Derivative FLC Kd

Figure 5.14 Fuzzy tuned Derivative Controller

Δe / $\Delta \dot{e}$	NB	NS	ZO	PS	PB
NB	NB	NB	NB	NS	ZO
NS	NB	NS	NS	ZO	NS
ZO	NB	NS	ZO	PS	PB
PS	NS	ZO	PS	PS	PB
PB	ZO	PS	PB	PB	PB

Figure 5.15 Rule base for all K_p, K_i, and K_d controller based on fuzzy tuning

5.4 Conclusion:

This chapter explains the active control of PAC system. In this chapter all the controllers namely PID, FLC, ANFIS, and Fuzzy PID were described.

CHAPTER VI

SIMULATION AND RESULTS OF ACTIVE CONTROLLERS FOR PAC SYSTEM

CHAPTER VI

SIMULATION AND RESULTS OF ACTIVE CONTROLLERS FOR PAC SYSTEM

Introduction

Studies related to the performance of active controllers designed for the PAC system is presented here. Simulations are performed on MATLAB R2011b on Intel Core i3-380M Processor 2.43 GHz. Window7 Home basic (64-bit) Laptop. The Contact Force is focused mainly for studying the performance of the controllers on PAC system.

Initially a comparative study based on different membership functions of fuzzy logic is carried out and best results are then compared with other conventional PID controllers and Artificial Intelligence techniques namely ANFIS and Fuzzy PID.

6.2 Fuzzy Logic Control (FLC) of PAC system

A comparative study of different mfs of FLC is carried out with PAC system. The effect of variable catenary stiffness is neglected. Firstly SISO FLC is designed with different mfs namely gauss, gbell, triangular and sigmoid. Fig 6.1 shows the simulink model of the PAC system for fuzzy logic controllers.

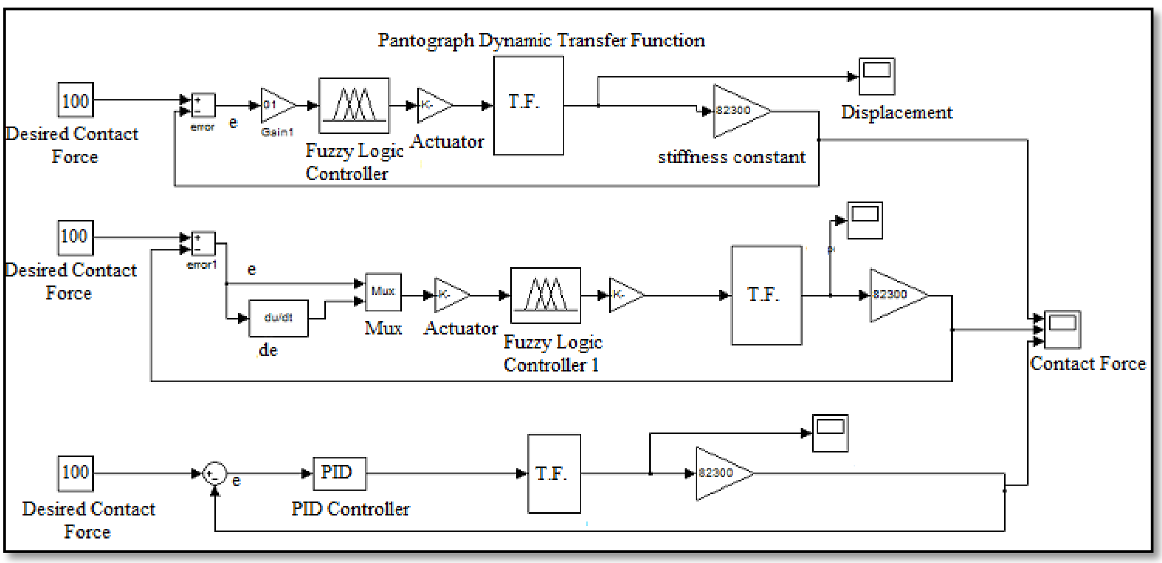
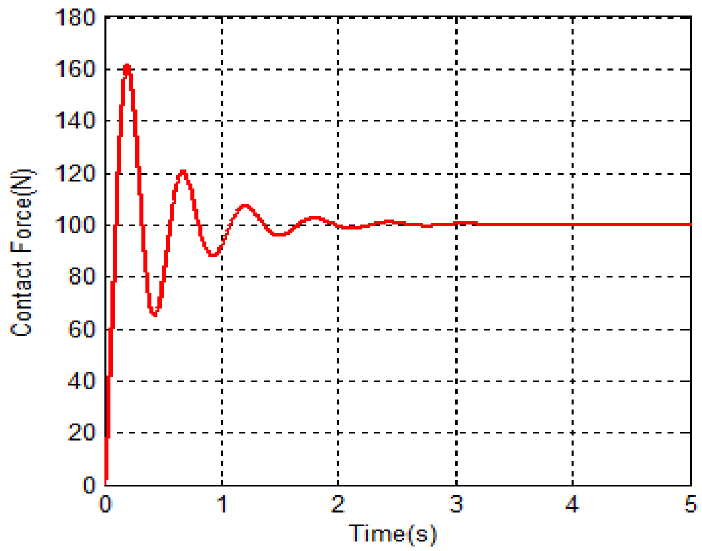


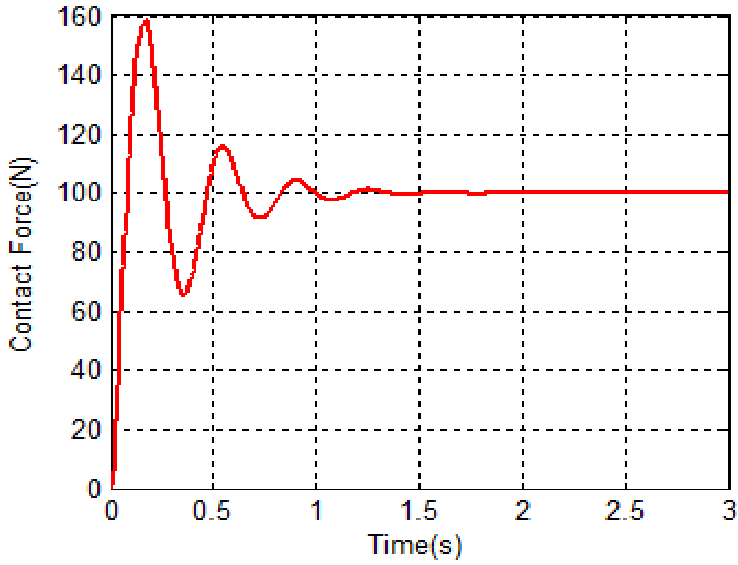
Figure 6.1 Simulink model of PAC system

The constant 100N force is given as the input to the PAC system. Fuzzy logic controllers are designed to maintain the force constant to 100N in closed loop condition.

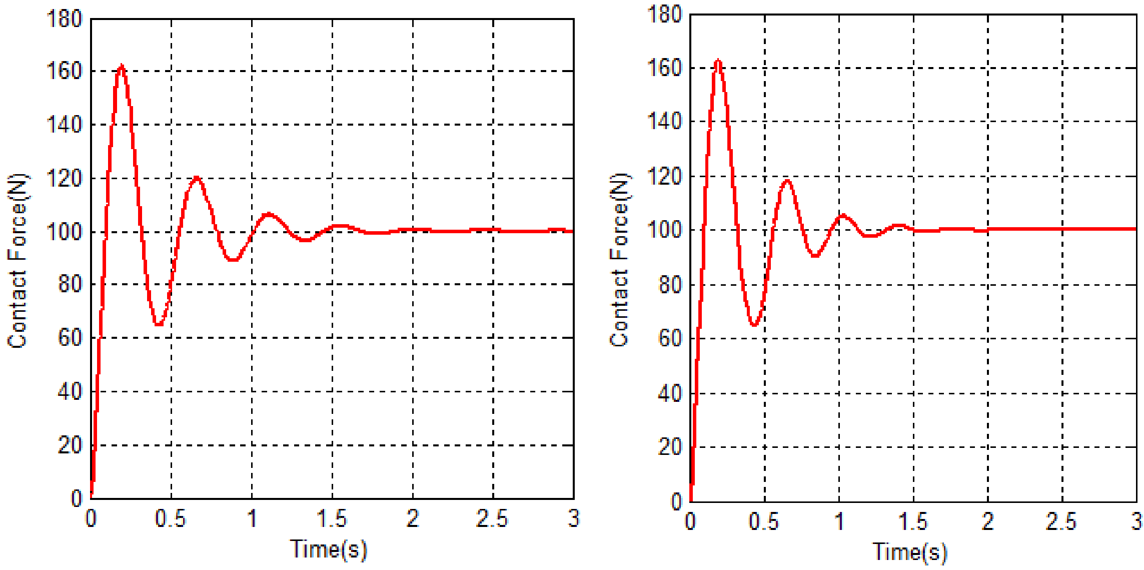
Fig. 6.2 (a-d) show the results of single input fuzzy logic controller with triangular, sigmoidal, gbell and gauss five input membership functions, respectively, It is observed that the response with sigmoidal membership function is best with less overshoot and settling time. So a fuzzy logic controller with seven membership function with gbell shape is also designed. It is observed that there is not much change in the response if the membership functions are increased to seven. The results for seven membership functions are as shown in Fig. 6.3 (a-b).



(a) Triangular functions

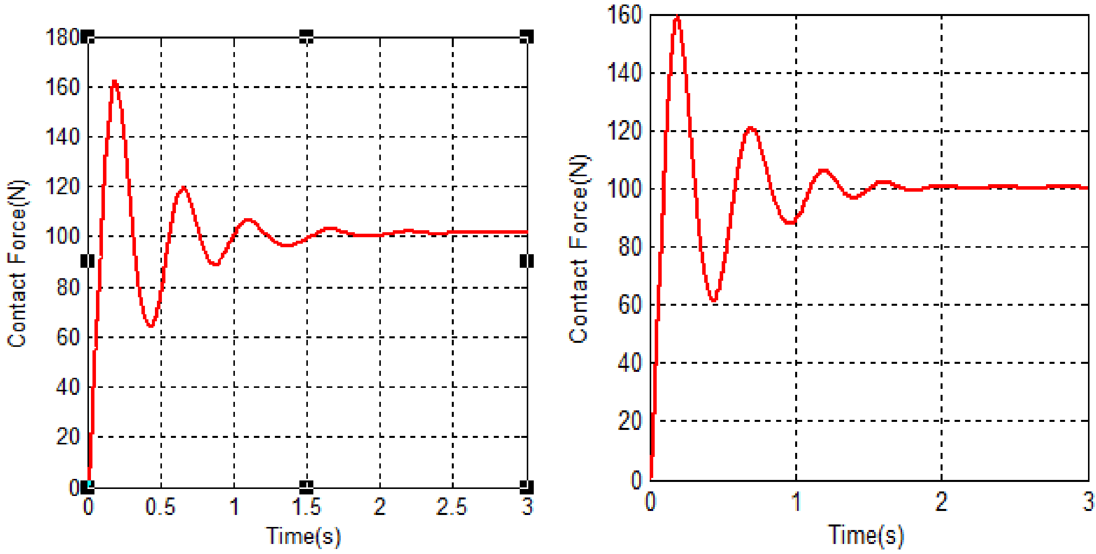


(b) Sigmoidal functions



(c) gauss functions (d) gbell functions

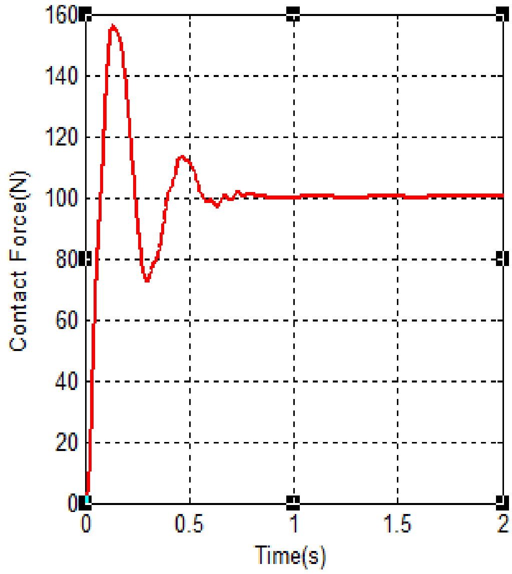
Figure 6.2 Response of single input fuzzy logic controller with five membership functions



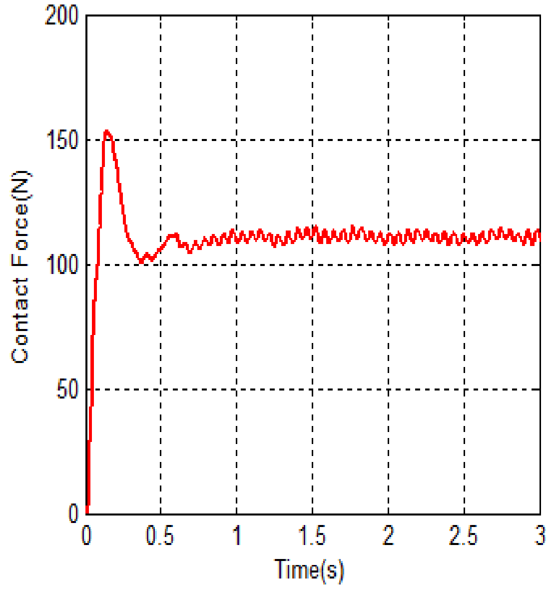
(a) triangular functions (b) sigmoidal functions

Figure 6.3 Response of single input fuzzy logic controller with seven membership functions.

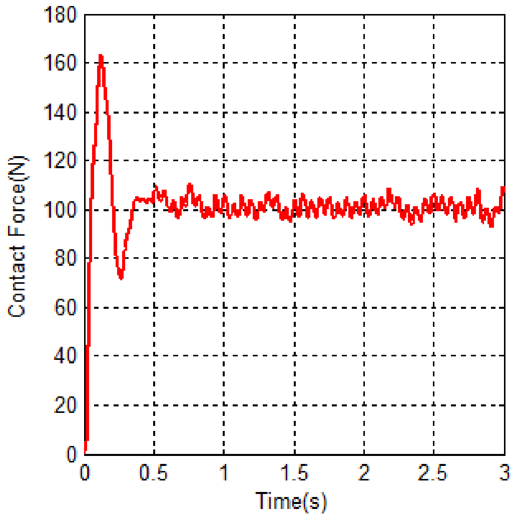
Further, the two input fuzzy logic controller using error and change in error is also designed. The membership functions used are triangular, gbell, gauss and sigmoid. The response is given by Fig.6.4. It is observed that for two inputs, the response is improved for each membership function with less overshoot and decrease in settling time though a small increase in noise is observed.



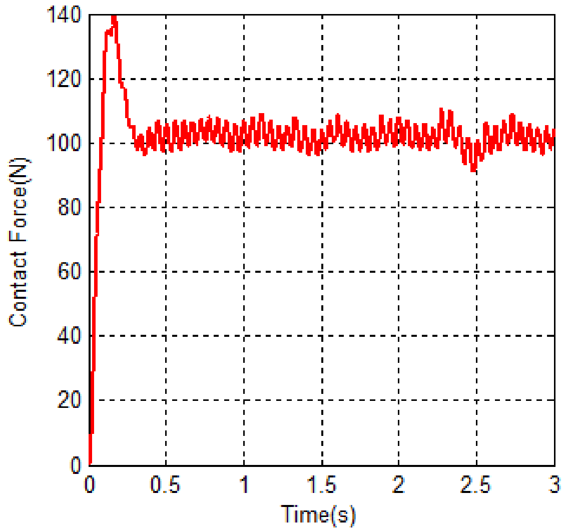
(a) Triangular functions



(b) Sigmoid functions



(c) Gauss functions



(d) Gbell functions

Figure 6.4 Response of two input fuzzy logic controller with five membership functions

The results for different types of controllers in terms of settling time and peak overshoot are given in table 6.1. It was observed that all the single input fuzzy logic controllers a very high settling time of approximately 1.5 sec and above with the least settling time in sigmoid mf which is approximately 1sec. But the settling time decreases to a very low value with two input FLC for all the membership functions. The least settling time of

0.3sec with lowest overshoot of 39% is observed in gbell mf though noise is observed in steady state which can be filtered out using filters.

TABLE 6.1

RESULTS OF DIFFERENT CONTROLLERS USED

Controller	Settling time	Peak Overshoot
Single input 5 mf (triangular)	1.65s	62.1%
Single input 5 mf(sigmoid)	0.99s	58.9%
Single input 5 mf(gauss)	1.47s	62.4%
Single input 5 mf(gbell)	1.51s	63.3%
Single input 7 mf(triangular)	1.87s	62.5%
Single input 7 mf(sigmoid)	1.72s	59.1%
Two input 5 mf (triangular)	0.56s	55.9%
Two input 5 mf(sigmoid)	0.36s	60%
Two input 5 mf(gauss)	0.35s	63.2%
Two input 5 mf(gbell)	0.3s	39.4%

6.3 Simulation of Active controllers for PAC system

The simulink model of an active PAC system with all the controllers used is shown in fig 6.5. Here the results of all the controllers are compared with the open loop system at two different speeds i.e. 150km/hr, and 200km/hr. In this model the mechanical transfer function derived in chapter 3 given by eq (3.6) is used for pantograph displacement oscillations and then using eq (3.7) catenary constant is multiplied to displacement output to measure the contact force.

Here a sine wave input of different magnitudes and frequency is used to denote the variable stiffness of the catenary at different train speeds. Sine wave of 10N with 3.63 Hz frequency is used for 150 km/hr speed and 15N magnitude at 4.85Hz frequency for 200km/hr speed. The response of open loop PAC system and all the controllers for 150km/hr are shown in fig 6.6 –fig 6.8.Table 6.2 shows the comparison of all controllers. The results are compared with respect to the peak overshoot (Mp %), settling time (Ts), and oscillations (%) for 150km/hr train speed.

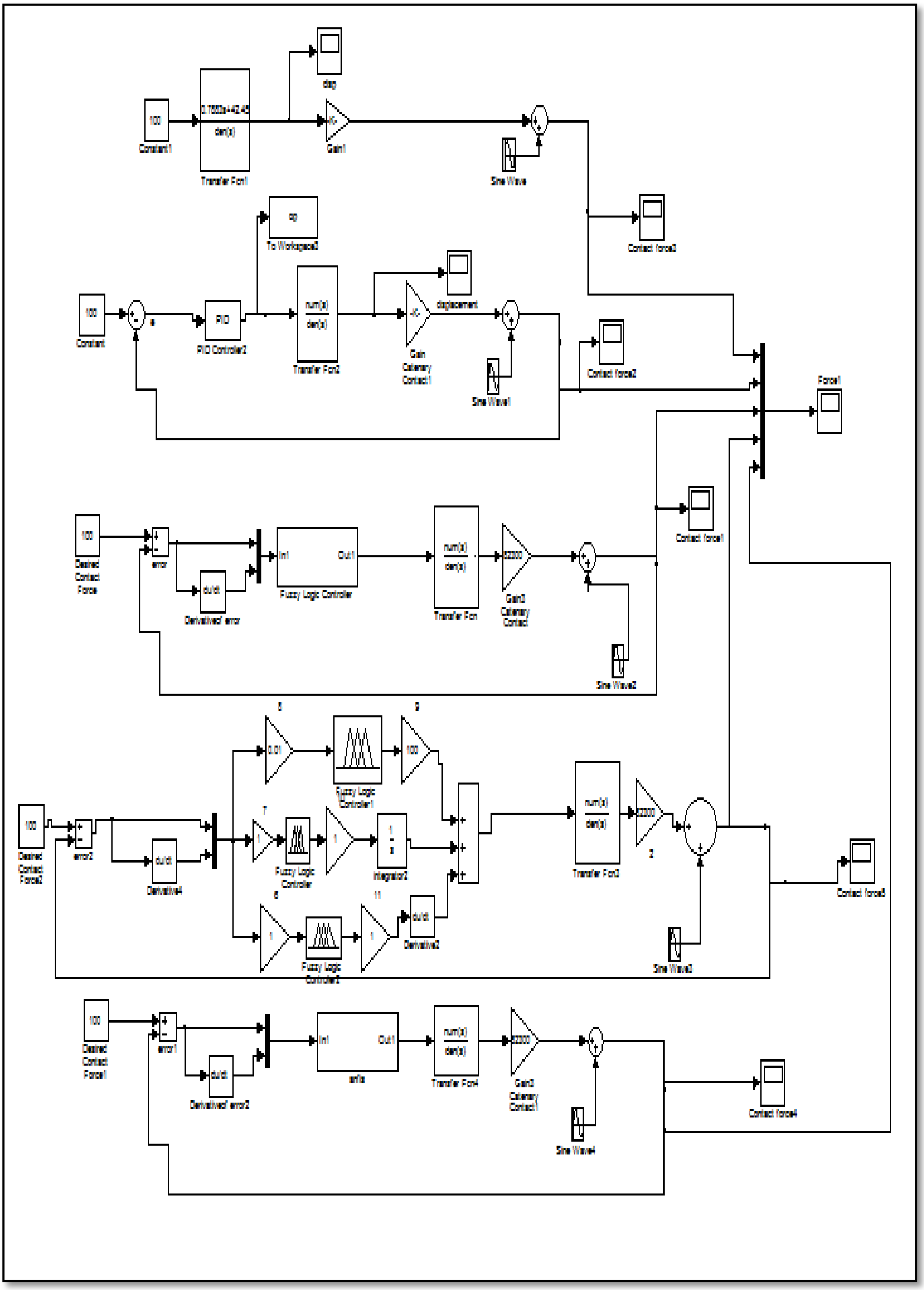


Figure 6.5 Simulink model of passive and active PAC system with all controllers

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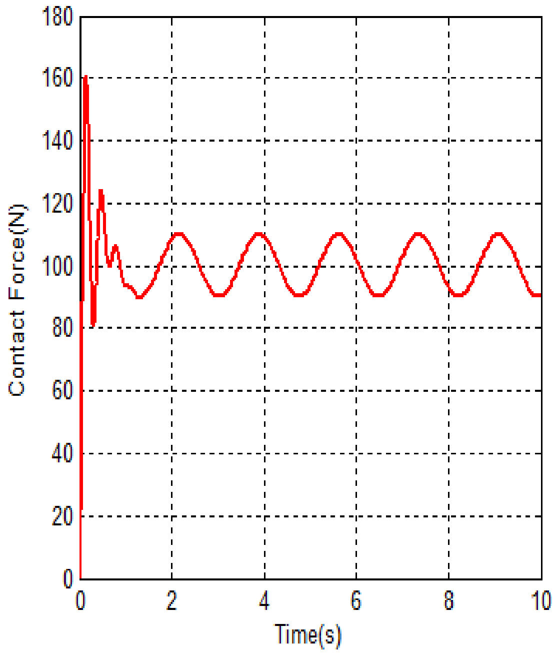
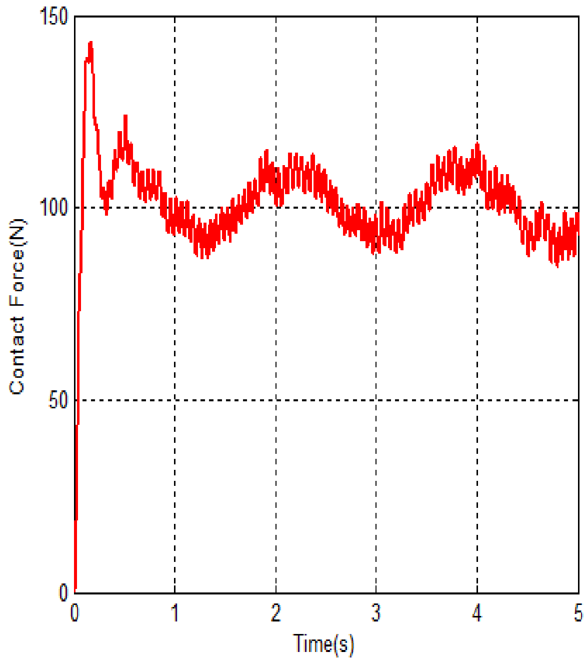
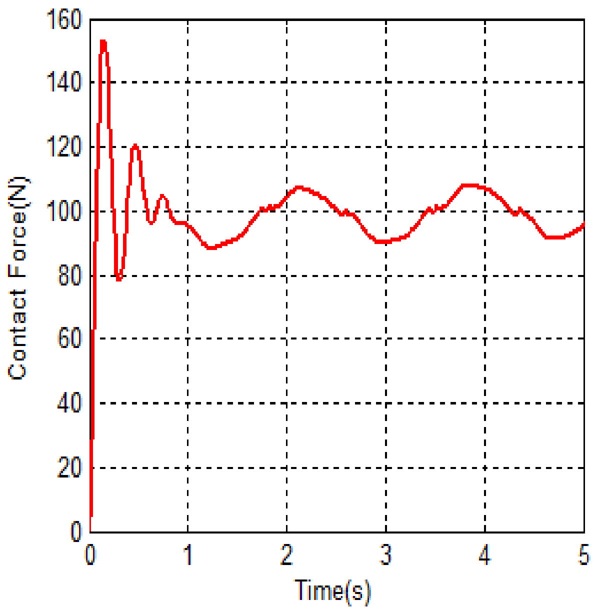


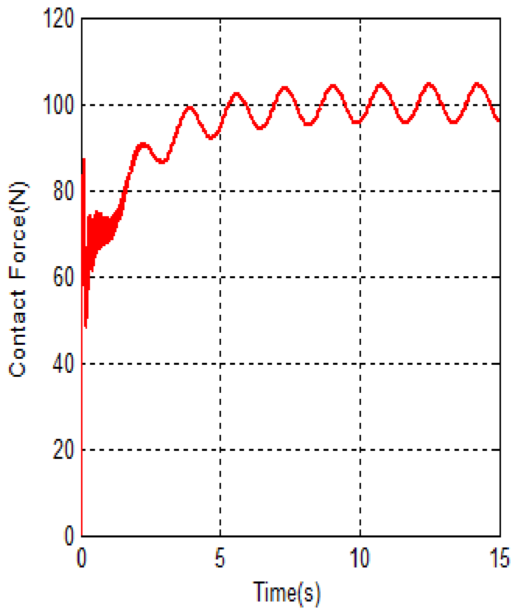
(a) Open Loop



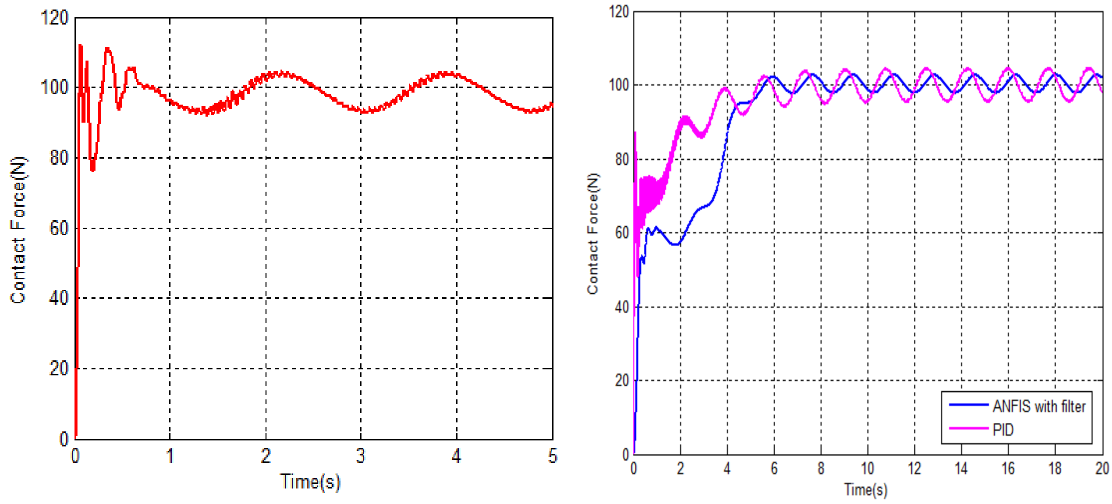
(b) Fuzzy Logic Control



(c) Fuzzy PID



(d) PID



(e) ANFIS (f) ANFIS with Filter

Figure 6.6 Response of all controllers for PAC system at 150km/hr

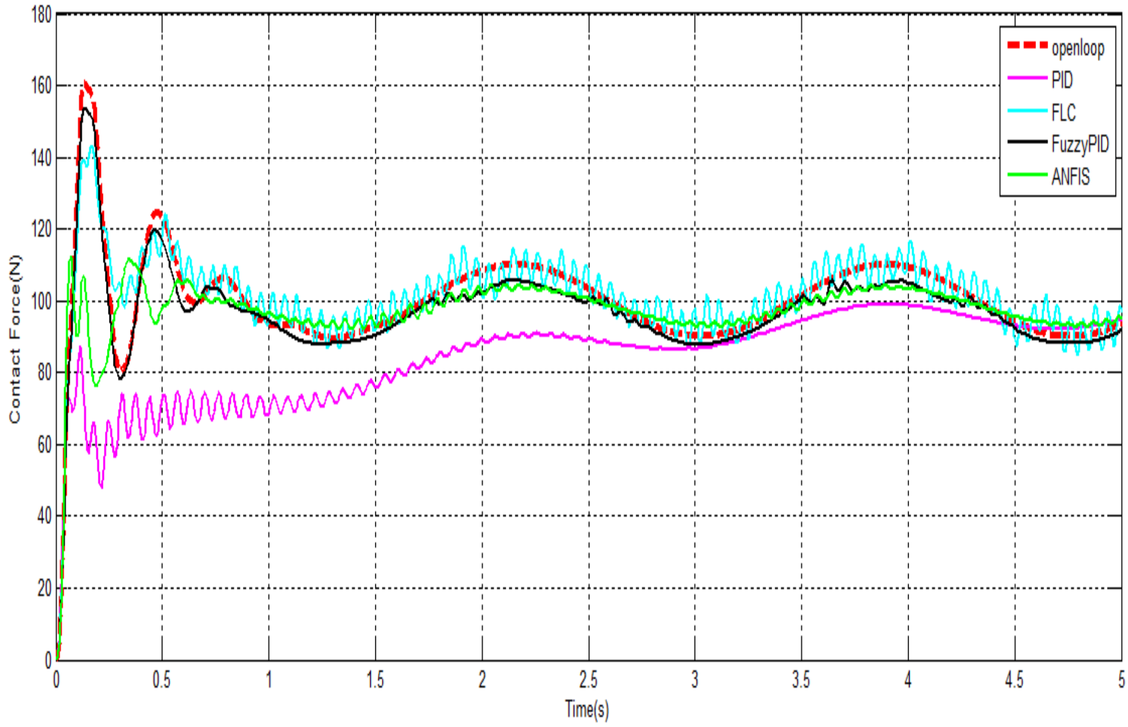


Figure 6.7 Transient responses of all controllers for PAC system at 150km/hr

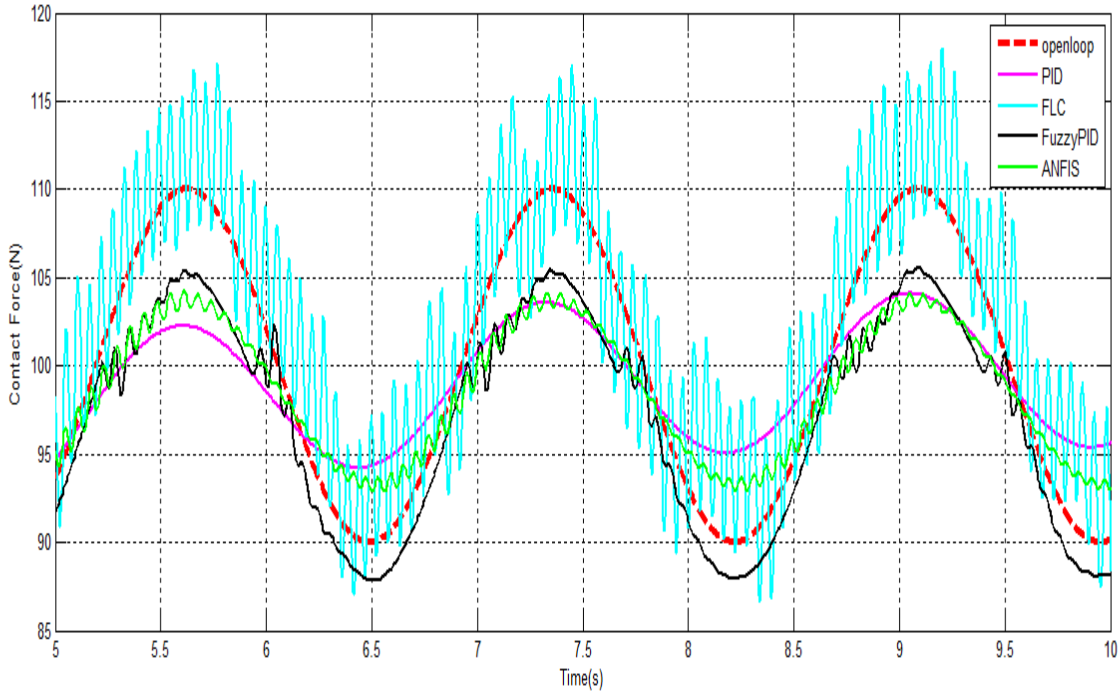


Figure 6.8 Steady state responses of all controllers for PAC system at 150km/hr

TABLE 6.2

COMPARISON OF ALL CONTROLLERS AT 150Km/hr

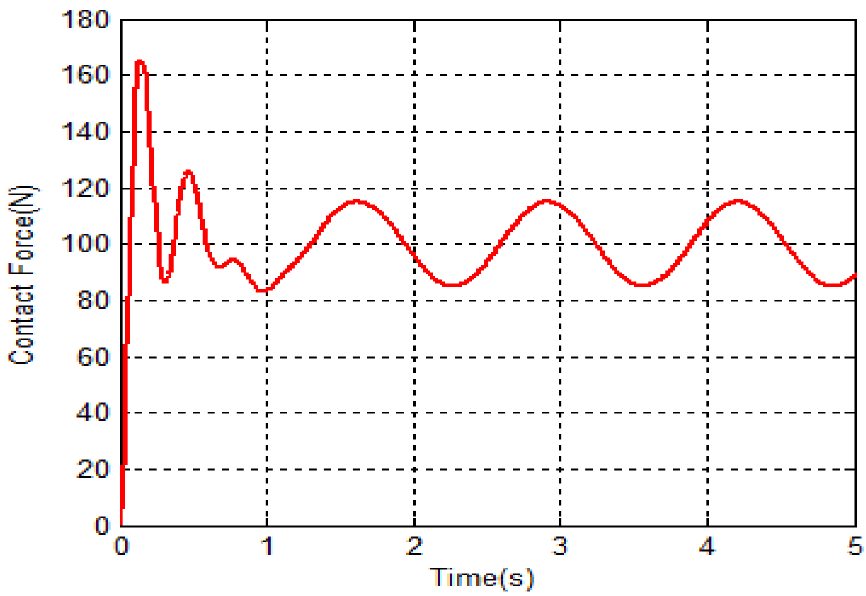
	Open Loop	PID	FLC	Fuzzy PID	ANFIS	ANFIS (with Filter)
Mp%	160	-	145	153.3	115.8	-
Ts(s)	1.8	5.3	1	0.8	0.9	4.2
Oscillations (%)	20	6	25	18	13	5

Table 6.2 shows that PID is giving a sluggish response with a settling time of 5.3sec but possess very less oscillations of only 6%. Here passive pantograph posses 20% oscillations that are provided to it in the form of catenary displacement variation at 150km/hr speed. PID is reducing those oscillations to only 6%, Fuzzy PID to 18% and ANFIS to 13% while

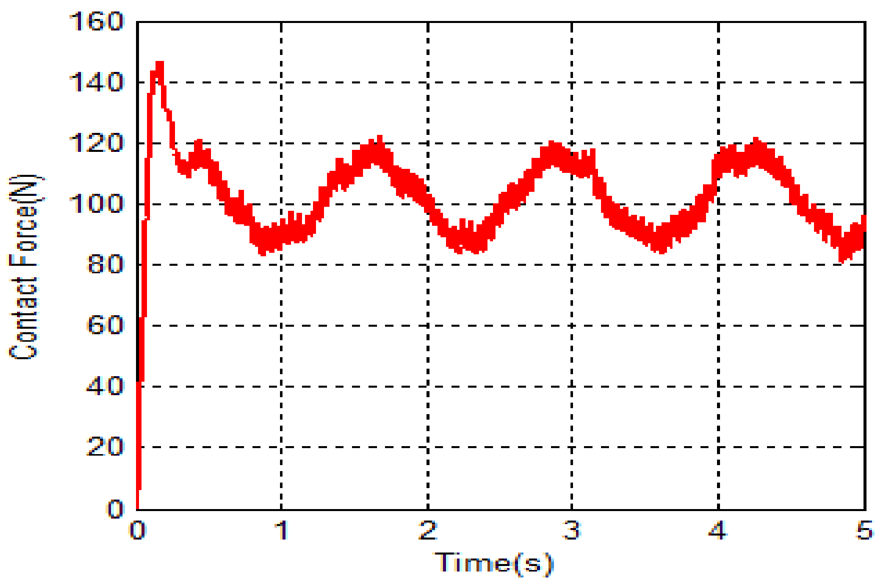
FLC is increasing them to 25%. Now comparing with respect to settling time as PID is having the most sluggish response and the least with Fuzzy PID and ANFIS controllers.

So it can be concluded that PID and ANFIS gives comparable outputs but ANFIS is better option as it possess lesser settling time and oscillations. Hence we connected a first order low pass filter across ANFIS and the oscillations are very much reduced to only 5%. Hence ANFIS controller is best feasible of all controllers used as shown in fig 6.6(f).

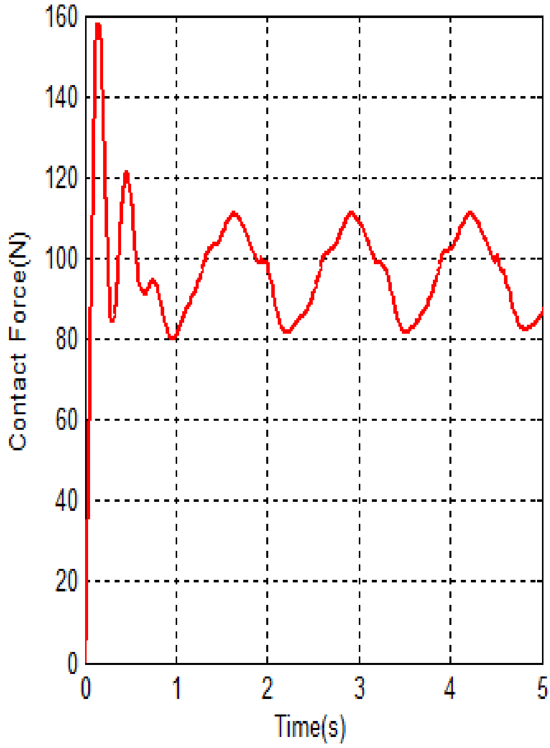
For 200km/hr speed the responses are shown in fig 6.9-6.11



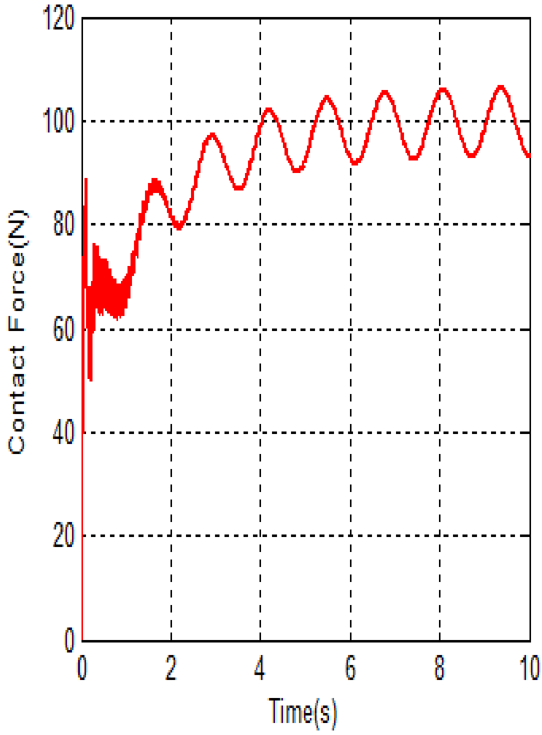
(a)Open loop



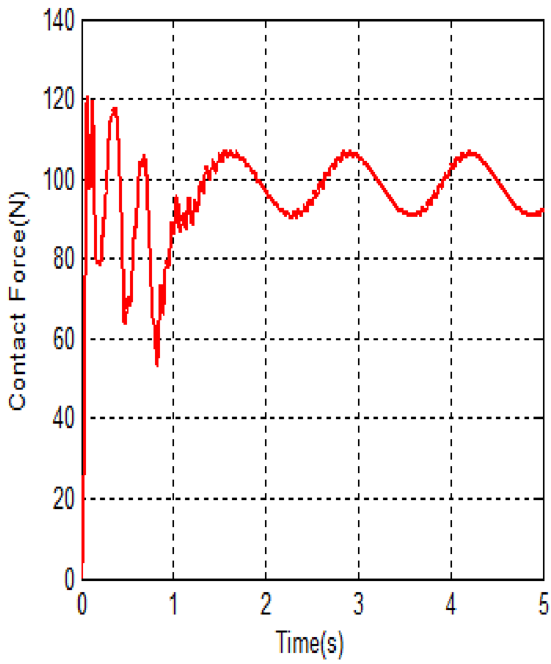
(b) Fuzzy Logic Control



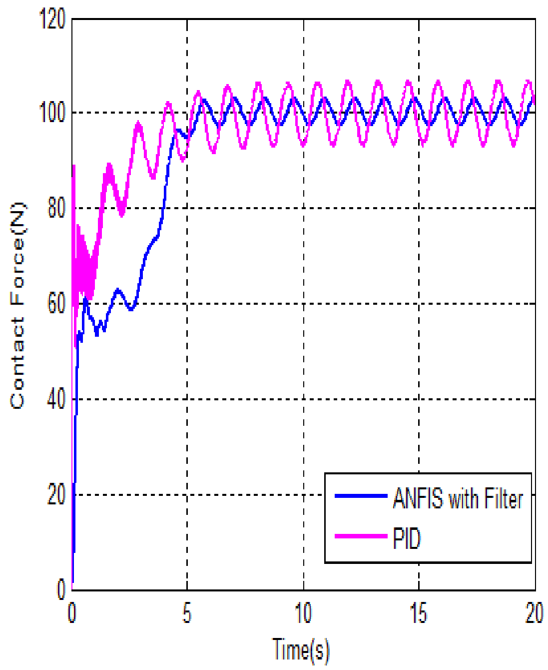
(c) Fuzzy PID



(d) PID



(e) ANFIS



(f) ANFIS with Filter

Figure 6.9 Response of all controllers for PAC system at 200km/hr

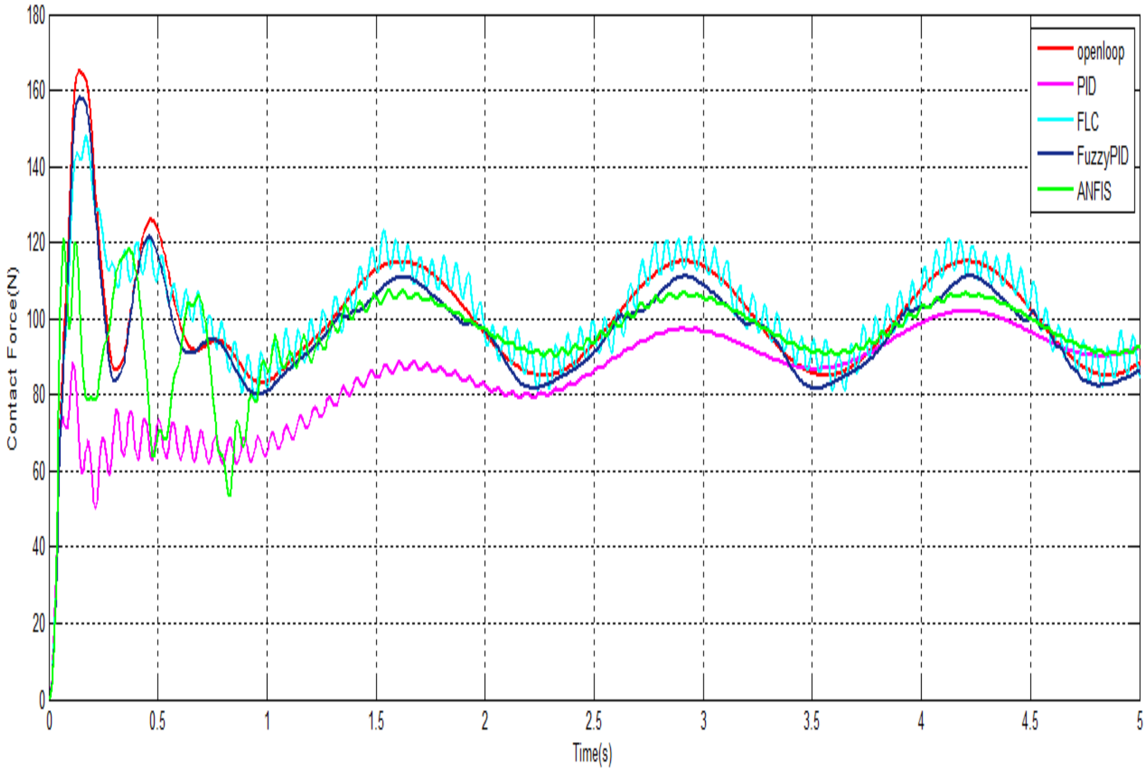


Figure 6.10 Transient responses of all controllers for PAC system at 200km/hr

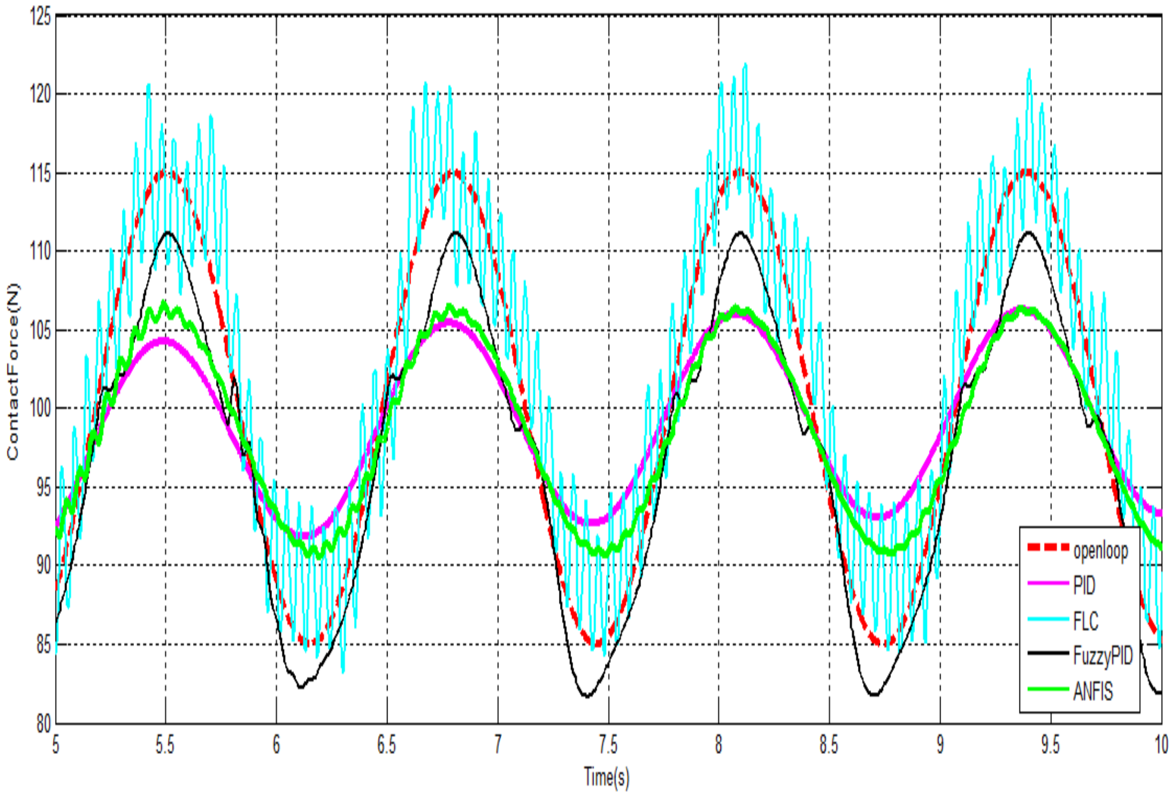


Figure 6.11 Steady state responses of all controllers including open loop PAC system at 200km/hr

TABLE 6.3

COMPARISON OF ALL CONTROLLERS AT 200Km/hr

	Open Loop	PID	FLC	Fuzzy PID	ANFIS	ANFIS (with Filter)
Mp%	165	-	145	155	120	-
Ts(s)	1.3	5.23	1.3	1.3	1.3	5.5
Oscillations (%)	30	13	25	30	15	6

Table 6.3 shows that PID is giving a sluggish response with a settling time of 4.3sec but posses very less oscillations of only 13%. Here passive pantograph posses 30% oscillations that are provided to it in the form of catenary displacement variation at 200km/hr speed. PID is reducing those oscillations to only 13%, FLC to 25% and ANFIS to 15% while Fuzzy PID is maintaining them to 30%. Now comparing with respect to settling time as PID is having the most sluggish response wrt FLC, Fuzzy PID and ANFIS controllers maintaining it to 1.3 sec as in open loop response.

So it can be concluded that ANFIS gives best outputs as it posses lesser oscillations. Hence ANFIS controller is best feasible of all controllers used. Hence we connected a first order low pass filter across ANFIS and the oscillations are very much reduced to only 6% making the system sluggish as shown in fig 6.9(f).

6.4 Conclusion

Here results of all the controllers were presented and compared with open loop PAC system. It was concluded that ANFIS gives better results in terms of oscillations and settling time and the peak overshoot.

CHAPTER VII

CONCLUSION AND FUTURE SCOPE

CHAPTER VII

CONCLUSION AND FUTURE SCOPE

7.1 Conclusion

Initially a mechanical model of the PAC system is developed and by using its defined parameters second-order system modeling techniques has been employed to develop simulink model of pantograph catenary system.

Further an Electrical analogous model of the mechanical model of the PAC system is developed and its hardware prototype is fabricated in the laboratory of Electrical Engineering Department, Delhi Technological University. The prototype of mechanical model of PAC system is difficult to develop in the laboratory conditions due to its heavy weight and large force involved. But its electric analogous prototype is simple in design and can be easily realized under test conditions. Further, the hardware electrical prototype model is found to be quite closer to the simulated mechanical model. This model once developed can be very useful for the system designer for the real time studies of the PAC system and can be used to design robust active controllers for the high speed trains.

Then a reduced order model is designed. The modeling of the reduced order transfer function has been successfully done using two techniques namely; approximation of higher order system by lower order system and order reduction using MATLAB programming method and the response is compared by integral square error. It was concluded that a third order transfer function can be replaced with the higher order transfer function with minimum ISE in order to reduce the complexity of the PAC system. These studies are found to be helpful for reducing complexity of the PAC system while maintaining its original properties.

Further fuzzy logic controller with the different membership functions and different numbers of inputs are designed for PAC system and the result is used further. It was seen that two input gbell shaped membership function gives good results with lesser over shoot but with noise and two input triangular membership function gives less settling time and no noise but high peak overshoot. Hence depending upon the requirement the best suitable FLC can be choosen.

The conventional PID controller and Artificial Intelligence techniques namely, ANFIS and Fuzzy PID with different membership function for PAC system have been designed and their responses are studied. The responses of all the controllers are then compared with the passive PAC system at two different speeds i.e.150km/hr and 200km/hr. It was observed that the response of PID controller is good having less oscillations but it possess sluggish settling time. Further with AI techniques mainly ANFIS provides better results comparable to PID at 150km/hr and better than PID at 200km/hr. ANFIS is then used with first order low pass filter. Hence it can be stated that with the further increase in speed ANFIS can be used considered better controller from all the controllers stated above. These studies will help in designing a better control scheme for a contact loss less pantograph-catenary system.

7.2 Future Scope of Work

There are several important points which needs to be investigated but could not be covered in this work due to the limited time frame. The following significant points need an immediate investigation for future works in order to take maximum advantage of this study.

- This study is based on 2DOF model, so further degree can be increased to 3DOF model for better insight of the performance of pantograph catenary system.
- The catenary stiffness is a function of speed hence the effect of speed variation (greater than 300km/hr) can be further investigated considering variable stiffness of catenary.
- The reduced order model can be validated using controllers.
- The Electrical hardware prototype can be further extended to close loop controlling schemes.
- A number of control techniques such as PSO and GA are available today that can be implemented for control of PAC system to further enhance the response for minimizing the loss of contact.

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1. Rachana Garg, Priya Mahajan, Parmod Kumar, Vidushi Gupta " **Electrical Prototype Model of Pantograph-Catenary System**" accepted in IEEE-TEC ASIA Pacific conference CHINA, 2014, to be published on IEEE Explorer.
2. Rachana Garg, Priya Mahajan, Parmod Kumar, Vidushi Gupta "**Design and Study of Active Controllers for Pantograph-Catenary System**" accepted in IEEE-TEC ASIA Pacific conference CHINA, 2014, to be published on IEEE Explorer.
3. Priya Mahajan, Rachana Garg, Vidushi Gupta, Parmod Kumar, "**Analysis of Pantograph-Catenary System by model order reduction**" presented in RAPS 2014, in PEC Chandigarh.