DESIGNING OF STATCOM CONTROLLERS FOR TRANSIENT STABILITY IMPROVEMENT OF TWO MACHINE SYSTEM

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In

POWER SYSTEMS & ELECTRICAL DRIVES

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CERTIFICATE

I hereby declare that the work which is presented in this thesis report, entitled, **"Designing of STATCOM Controllers for Transient Stability Improvement of Two Machine System."** in partial fulfilment of the requirements for the awards of the Master's degree in Power Systems & Electrical drives, submitted in Electrical and Instrumentation Engineering Department, Thapar University, Patiala, is an authentic record of initial work carried out under the supervision of Mr. Shakti Singh, EIED and Mr. Vikram, EIED, THAPAR UNIVERSITY, PATIALA.

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ABSTRACT

Transmission networks of modern power systems are becoming increasingly stressed because of growing demand and restrictions on building new lines. One of the consequences of such a stressed system is the threat of losing stability following a disturbance. Flexible ac transmission system (FACTS) devices are found to be very effective in a transmission network for better utilization of its existing facilities without sacrificing the desired stability margin. Flexible AC Transmission System (FACTS) such as Static Synchronous Compensator (STATCOM) and Static VAR Compensator (SVC), employ the latest technology of power electronic switching devices in electric power transmission systems to control voltage and power flow. A static synchronous compensator (STATCOM) is a shunt device of the flexible AC transmission systems (FACTS) family . The STATCOM regulates voltage at its terminal by controlling the amount of reactive power injected into or absorbed from power system. When system voltage is low, STATCOM generates reactive power and when system voltage is high it absorbs reactive power. In this Thesis different STATCOM controllers i.e. based on Fuzzy Logic, Fuzzy-PI and ANFIS based are designed for improving transient stability of two machine systems. Proposed controllers are implemented under MATLAB/SIMULNK environment. Results of Fuzzy based and Fuzzy-PI based controllers installed with two machine system compared with conventional PI based STATCOM controller.

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LIST OF ACRONYMS

AC	Alternating Current
DC	Direct Current
IEEE	Institute of Electrical and Electronics Engineers
FACTS	Flexible Alternating Current Transmission System
STATCOM	Static Synchronous compensator
VSC	Voltage Source Converter
GTO	Gate Turn-off Thyristor
IGBT	Insulated Gate Bipolar Transistor
SVC	Static Var Compensator
FL	Fuzzy Logic
COA	Centre of Area
PI	Proportional Integral
NVB	Negative Very Big
NB	Negative Big
Z	Zero
PB	Positive Big
PVB	Positive Very Big
ANFIS	Adaptive Network Fuzzy Inference System

LIST OF SYMBOLS

V_{out}	AC output voltage
V_{dc}	Voltage across dc capacitor
I_{ac}	STATCOM output ac current
Q	Reactive power
P	Active power
V_{ac}	AC system bus voltage
α	Firing angle
M	Angular moment of rotor
J	Moment of inertia of rotor
ω	Generator speed
P_s	Mechanical power input
P_e	Electrical power
P_a	Accelerating power
δ_c	Critical clearing angle
δ_0	No load angle
H	Inertia constant
A_1	Area of acceleration
A_2	Area of deceleration
$\frac{d\omega}{dt}$	Rate of change of generator speed
e	Error
$\frac{de}{dt}$	Rate of change of error
K_p	Proportional gain
K_i	Integral gain
V_{meas}	Measured voltage of STATCOM
V_{ref}	Reference voltage of STATCOM
I_q	Measured current of STATCOM
I_{q_ref}	Reference current of STATCOM
V_aSec	Transformer secondary voltage
$V_a\,, I_a$	Voltage and Current of bus B2

CHAPTER 1

INTRODUCTION

1.1 Introduction

Modern electric power system is facing many challenges due to day by day increasing complexity in their operation and structure. In the recent past, one of the problems that got wide attention is the power system instability. With the lack of new generation and transmission facilities and over exploitation of the existing facilities geared by increase in load demand make these types of problems more imminent in modern power systems. Demand of electrical power is continuously rising at a very high rate due to rapid industrial development [1].

To meet this demand, it is essential to raise the transmitted power along with the existing transmission facilities. The need for the power flow control in electrical power systems is thus evident. With the increased loading of transmission lines, the problem of transient stability after a major fault can become a transmission power limiting factor. The power system should adapt to momentary system conditions, in other words, power system should be flexible. In an ac power system, the electrical generation and load must balance at all times up to some extent, the power system is self regulating .If generation is less than load ,the voltage and frequency drop, and thereby the load goes down to equal the generation minus transmission losses. But there are only a few percent margins for such a self regulation. Hence there is chance of system collapse. Generator excitation controller with only excitation control can improve transient stability for minor faults but it is not sufficient to maintain stability of system for large faults occur near to generator terminals [17]. Thus, this requires a review of traditional methods and the creation of new concepts that emphasize a more efficient use of already existing power system resources without reduction in system stability and security. In the late 1980s, the Electric Power Research Institute (EPRI) introduced a new approach to solve the problem of designing and operating power systems; the proposed concept is known as Flexible AC Transmission Systems (FACTS). The two main objectives of FACTS are to increase the transmission capacity and control power flow over designated transmission routes.

FACTS are defined by the IEEE as "a power electronic based system and other static equipment that provide control of one or more AC transmission system parameters to enhance controllability and increase power transfer capability.

Basically, FACTS controllers can be divided into four categories [2]:

1) Series Controller
2) Shunt Controller
3) Combined series-series Controller
4) Combined series-shunt Controller

Table 1.1: Comparison among FACTS Controllers [2].

Name	**Type**	**Controller Used**	**Purpose**
STATCOM	Shunt	GTO	Voltage Control
SVC	Shunt	Thyristor	Voltage Control
SSSC	Series	GTO	Power flow Control
TCSC	Series	Thyristor	Power flow Control
UPFC	Shunt and Series	GTO	Voltage and Power flow Control
TCPAR	Series and Series	Thyristor	Power flow Control

Typical applications of FACTS in power system are [2]:

1) Effective voltage regulation and control.
2) Reduction of temporary overvoltage.
3) Improvement of steady-state power transfer capacity
4) Damping of power system oscillations.
5) Power quality improvement.

1.2 Static Synchronous Compensator (STATCOM)

"A Static synchronous compensator is a shunt-connected static var compensator whose capacitive or inductive output current can be controlled independent of the ac system voltage"[1]

The concept of STATCOM was proposed by Gyugyi in 1976. Power Converter employed in the STATCOM mainly of two types i.e. is Voltage Source Converter and Current Source

Converter. In Current source Converter direct current always has one polarity and the power reversal takes place through reversal of dc voltage polarity while In Voltage Source Converter dc voltage always has one polarity, and the power reversal takes place through reversal of dc current polarity. The power semiconductor devices used in current source converter requires bidirectional voltage blocking capability and for achieving this Characteristic an additional diode must be connected in series with a semiconductor switch which increased the system cost and its becomes costlier as compared to voltage source converter moreover Voltage source converter can operate on higher efficiency in high power applications. Because of the above reasons Voltage source converter is Preferred over Current source converter and now these days it act as a basic electronic block of a STATCOM that converts a dc voltage at its input terminals into a three-phase set of ac voltages at fundamental frequency with controllable magnitude and phase angle [1].

In STATCOM different technologies used dependent upon the power ratings of STATCOM. For higher power STATCOMs GTO based technologies are used while for lower power STATCOMs IGBT based technologies used.

1.3 Operating Principle of STATCOM

STATCOM is made up of a coupling transformer, a VSC and a dc energy storage device. STATCOM is capable of exchanging reactive power with the transmission line because of its small energy storage device i.e. small dc capacitor, if this dc capacitor is replaced with dc storage battery or other dc voltage source, the controller can exchange real and reactive power with the transmission system, extending its region of operation from two to four quadrants. A functional model of a STATCOM is shown in Figure 1.1

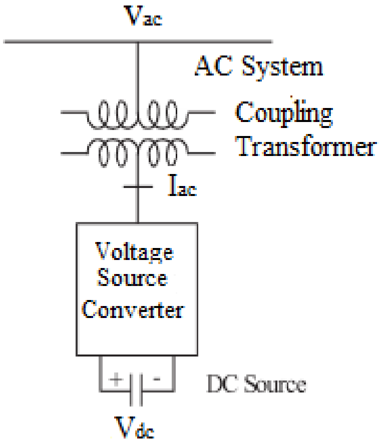

Figure 1.1 Functional model of STATCOM [1]

The relationship between fundamental component of the converter ac output voltage and voltage across dc capacitor is given as

$$V_{out} = kV_{dc}$$

Where k is coefficient which depends upon on the converter configuration, number of switching pulses and the converter controls. The fundamental component of the converter output voltage i.e. V_{out} can be controlled by varying the dc voltage across capacitor which can be done by changing the phase angle α of the operation of the converter switches relative to the phase of the ac system bus voltage. The direction of flow of reactive power whether it is from coupling transformer to the system or from system to the coupling transformer depends upon the difference between the converter output voltage and the ac system bus voltage. The real power flowing into the converter supplies the converter losses due to switching and charges the dc capacitor to a satisfactory dc voltage level. The capacitor is charged and discharged during the course of each switching cycle but in steady state, the average capacitor voltage remains constant. If that were not the case, there would be real power flowing into or out of the converter, and the capacitor would gain or lose charge each cycle. In steady state, al1 of the power from the ac system is used to replenish the losses due to switching. The STATCOM's ability to absorb/supply real power depends on the size of dc capacitor and the real power losses due to switching. Whenever the dc capacitor and the losses are relatively small. The amount of real power transfer is also relatively small. This implies that the STATCOM’s output ac current I_{ac}, has to be approximately + 90^0 with respect to ac system voltage at its line terminals. Varying the amplitude of the converter three-phase output voltage V_{out} controls the reactive power generation/absorption of the STATCOM. If the amplitude of the converter output voltage V_{out} is increased above the amplitude of the ac system bus voltage V_{ac} then the ac current I_{ac}, flows through the transformer reactance from the converter to the ac system generating reactive power. In this case, the ac system draws capacitive current that leads by an angle of 90^0 the ac system voltage, assuming that the converter losses are equal to zero. The ac current flows from the ac system to the voltage-sourced converter if the amplitude of the converter output voltage is decreased below that of the ac system, and consequently the converter absorbs reactive power. For an inductive operation, the current lags the ac voltage by an angle of 90^0. Assuming again that the converter losses are neglected. If the amplitudes of the ac system and converter output voltages are equal, there will be no ac current flow in/out of the converter and hence there will be no reactive power generation/absorption the ac current magnitude can be calculated using the following equation

$$I_{ac} = \frac{V_{out} - V_{ac}}{X} \tag{1.1}$$

Assuming that the ac current flows from the converter to the ac system. V_{out} and V_{ac} are the magnitudes of the converter output voltage and ac system voltage respectively, while X represents the coupling transformer leakage reactance. The corresponding reactive power exchanged can be expressed as follows:

$$Q = \frac{V_{out}^2 - V_{out}V_{ac}\cos\alpha}{X} \tag{1.2}$$

The real power exchange between the voltage-sourced converter and the ac system can be calculated using:

$$P = \frac{V_{ac}V_{out}\sin\alpha}{X} \tag{1.3}$$

1.4 Operating Modes

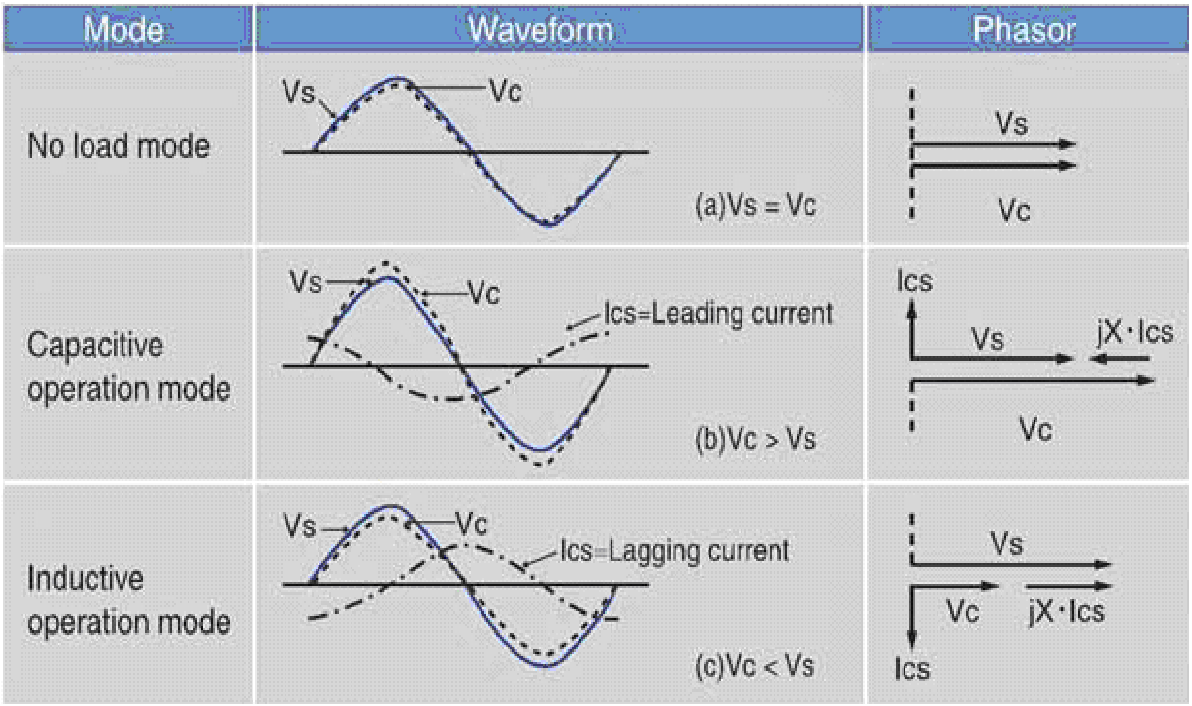

Figure 1.2 Operating modes of STATCOM [2]

1.5 Major Advantages of STATCOM over SVC are

1) In STATCOM, maximum inductive or capacitive current can be maintained independently of the ac system voltage and the maximum var generation or absorption changes linearly with ac system voltage while in SVC maximum inductive or capacitive current decreases linearly with system ac voltage and maximum var output decreases with the square of voltage. I.e. why STATCOM is better than SVC in providing voltage support under large disturbances.
2) STATCOM is more effective than SVC in improving transient stability of system because of its ability to maintain full capacitive output current at low system voltage.
3) Response time is better than SVC.
4) Active power control is possible in STATCOM
5) Installation space requirement of STATCOM is lesser as compared to SVC [1] [2][3].

1.6 V-I Characteristics of STATCOM

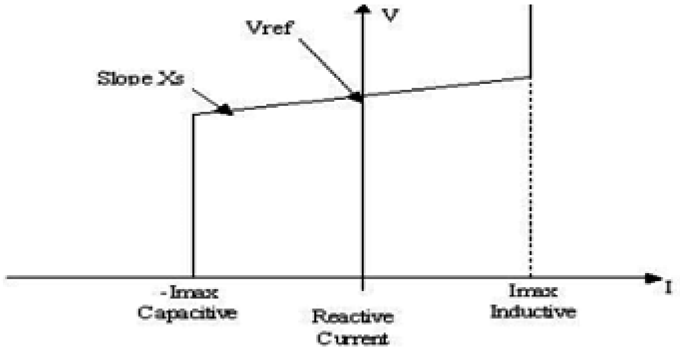

Figure 1.3 V-I Characteristics of STATCOM [1]

When the STATCOM is worked in voltage regulation mode, It implements the V-I characteristics as shown. The V-I characteristics are depicted by the following equation:

$$V = V_{ref} + X_s \cdot I$$

Where

V = Positive sequence voltage

I = Reactive current (pu/P_{norm})

(I > 0 indicates an inductive current and I < 0 indicates capacitive current)

X_s = Slope (usually between 1% and 5%)

P_{norm} = Converter rating in MVA

1.7 Literature Review

Schauder, et *al*. proposed a vector control scheme for control of reactive current using STATCOM [4]. They described two controller structures for the STATCOM one of which involves both magnitude and phase control of inverter, and the other structure uses only phase angle control. For the latter controller structure the system is not amenable to linear output feedback controller in all operating regions. Authors proposed a nonlinear state feedback controller to overcome this problem. **Laszlo Gyugyi**, *et a*l. gave the basic concept of STATCOM using voltage-source converter in [5]. The basic operation of STATCOM and the functional control scheme to control the STATCOM used for both reactive and real power compensation are given in this paper. Study of multilevel topologies of STATCOM has been presented in [6] [7]. The thyristor controlled STATCOM with new double firing phase control which makes it possible to control the active and the reactive power directly and independently without any sacrifice of the harmonic characteristic is presented in [8].

Design of voltage controller and the analysis of its dynamic behaviour using Eigen value analysis and its simulation are presented in [9] the paper concentrates on the application of STATCOM for the reactive power compensation of a long transmission line by regulating the voltage at its midpoint. It has been found that the plant transfer function is of the minimum phase type. Eigen value analysis using linearized model was carried out to design a compensator in cascade with an integral controller to overcome this problem. Design of a nonlinear controller for STATCOM based on the differential algebra theory is presented in [10]. The controller designed by this method allows linearizing the compensator and controlling directly the capacitor voltage and output reactive power of the STATCOM. Such a control enables to stabilize the compensation system and thus helps to improve largely the transient performance of the global system. A rule based controller for STATCOM was proposed in [11]. The paper analyzes the synchronizing and damping torque induced on the shaft of the generator by STATCOM in a single machine infinite bus (SMIB) system. It was found that the induced damping torque always decreases with the strengthening of the voltage control. Moreover, a fixed parameter PI damping controller can be invalid or even provide the system with negative damping for certain system parameters and load conditions. Based on the synchronizing and damping torque coefficient calculation, a rule based controller, which employs bang bang, fuzzy logic or fixed parameter PI control strategy according to operation state of the system is designed to compromise the conflict between the control objectives. **M.Moaddies**, *et al*. [12] described a technique to control the harmonic output of a STATCOM using a PWM scheme with a minimal number of additional switching. A neural network algorithm was developed to define the switching instants. The techniques seem to offer a better alternative to other conventional methods. Fuzzy logic controllers are also used for STATCOM in interconnected system to improve the dynamic behaviour of the system [13]. a robust non linear controller is proposed for STATCOM voltage control in [14]. Direct feedback linearization technique was employed to transform the nonlinear model into a linear one. The Riccati equation approach is then used to design the robust controller for the linearized model. Simulation studies show that in addition to the true system parameters, the bounds of the plant unknown time-varying parameters are also needed for the design and the overall system was found to be asymptotically stable for all admissible uncertainties. **Pranesh Rao**, *et al*. [15] compared the conventional method of PI controller with various feedback controller strategies and was found linear optimal statcom controller based on LQR control superior in terms of response, profile & control.**M.M. Farsangi**, *et al*. designed STATCOM controller based on Hinf loop shaping method in [16] and found that it's more effective as compared to traditional controller. **L Cong**, *et al.* in [17] gave a non-linear model of STATCOM installed in Power System and with help of robust control theory STATCOM controller is designed (based on the variation of structure, the parameter uncertainties and interconnection between the generator and STATCOM). This non-linear controller was found to be effective over a wide range of operating conditions and ensures the co-ordinated operation of STATCOM and the generator excitation.

In [18] a STATCOM controller based on hamilonian control theory proposed by **Q.J.Liu**, *et.al*, for multimachine power system stability enhancement and found by using this controller the non-linearity and interconnection of the overall system can easily be solved. A non-linear state feedback controller designed for regulation of output voltage in [19] by **Amit K Jain**, *et al.* and it was found that this controller shows good transient response for step changes in load conductance and reference voltage as well as significant flicker mitigation. STATCOM instability analyzed and a new automatic gain controller proposed to ensure the stable operation of the STATCOM under various load conditions in [20]. **Hui Li**, *et al*. designed a STATCOM controller based on superconductive Magnetic energy storage (SMES) in [21] and simulation results showed that fast response can be achieved in both d.c quantity and reactive power control. **Amit Jain**, *et al.* [22] designed a Linear and Non-Linear STATCOM controllers for improvement of regulation problem and it was shown that the Non-Linear STATCOM controller gave better transient response for load changes and leads to better mitigation of flicker arising from time varying loads. **Salman Mohaghegi**, *et al.* [23] designed a Neuro fuzzy external STATCOM controller for 12 bus benchmark power systems and it was found that the proposed neuro fuzzy external controller is more effective for damping the speed deviations of the generators near to STATCOM. In [24] again **Salman Mohaghegi**, *et al.* proposed an optimal neuro-fuzzy external controller for STATCOM in a multimachine power system. A zero order Takagi sugeno fuzzy rule base constitutes the core of the controller.

In [25] **Salman Mohaghegi**, *et al.* implemented a Mamdani fuzzy logic controller on a digital signal processor board and used for different controllable components in the network. It was found that Mamadani fuzzy logic STATCOM controllers provide better damping compared to the conventional PI controller and its also utilize its current capacity in more effective yet economical way.

Mohamad S, *et al.* [26] designed STATCOM controller based on Novel damping control algorithm for series compensated Wind Park for mitigating SSR and damping power system oscillations. Simulation results demonstrate that Novel STATCOM controller improves the transient stability margin. **Chien Hung Liu** *et al.* designed a self tuning STATCOM PI controller using particle swarm optimization [27]. It was found that satisfactory dynamic responses can be reached by the proposed self tuning controller under various loading conditions. **Vita aly Spitsa**, *et al.* [28] introduced zero set concepts for designing feedback controller for STATCOM. **Li-Wang**, *et al.* proposed a damping controller of the STATCOM using model control theory to contribute effective damping characteristics to the studied system under different operating conditions in [29] and it was found that proposed STATCOM controller joined with the designed PID damping controller is capable of improving performance of studied system. **Keyou Wang** *et al.* [30] proposed a new internal STATCOM control based on feedback linearization. Simulation results show that the proposed control exhibits more effective performance regardless of operating condition including small load change, large load change and three phase short circuits, when compared with traditional PI controls.

1.8 Objective of the Thesis

The main objective of this Thesis is:

- To design Fuzzy based STATCOM controller for two machine system and compare it’s performance with conventional PI based STATCOM controller
- To develop Fuzzy-PI based STATCOM controller for two machine system and compare its performance with conventional PI based STATCOM controller.
- To design ANFIS based STATCOM controller

1.9 Organization of the Thesis

The chapter wise summary of the work reported as follows:

Chapter 2 Covers the basic of Power system stability.

Chapter 3 Addressed the concepts of designing of different STATCOM controller’s i.e. fuzzy logic controller, fuzzy-pi based controller and ANFIS based controller. All are designed under MATLAB/ SIMULINK environment.

Chapter 4 Presents the simulation results of two machine systems installed with Fuzzy based, Fuzzy-PI based and ANFIS based STATCOM controller and compare results of Fuzzy based and Fuzzy-PI based STATCOM controllers with conventional PI based STATCOM controller.

Chapter 5 Presents the conclusion of thesis.

CHAPTER 2

POWER SYSTEM STABILITY

2.1 Introduction

Power System stability may be defined as the property of power system to remain in a state of operating equilibrium under normal operating conditions and regain an acceptable state of equilibrium after being subjected to a disturbance [31]. Broadly Stability is classified in to

1) Rotor angle Stability
2) Frequency Stability
3) Voltage Stability

In this chapter over emphasis is on Rotor angle stability aspect of power system.

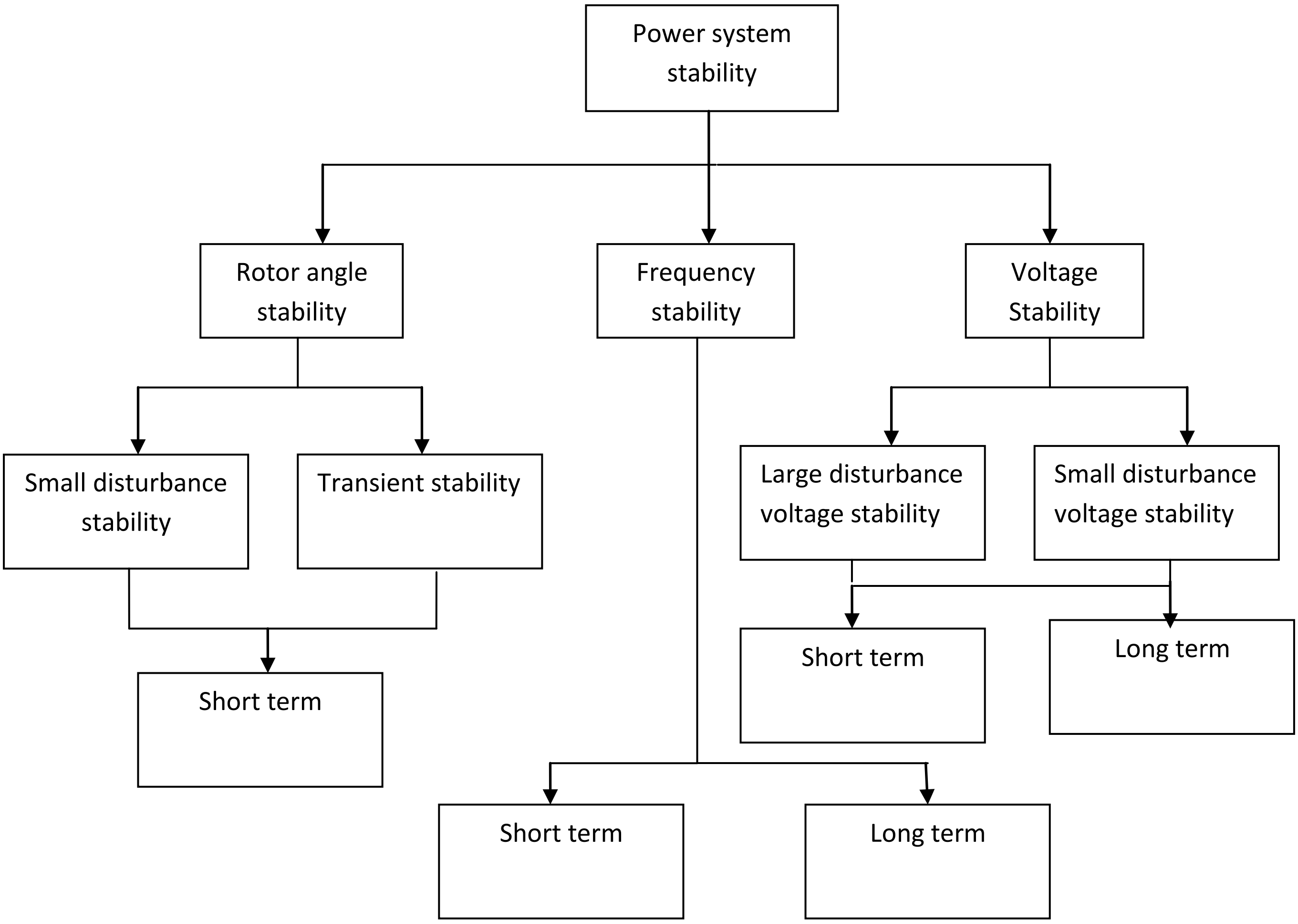

Figure 2.1 Classification of Power System Stability [32]

2.2. Rotor Angle Stability

It refers to ability of synchronous machine of an interconnected power system to remain in synchronism after being subjected to disturbance. It depends upon ability of each machine to maintain equilibrium between their electromagnetic torque and mechanical torque. The fundamental factor in this problem is that how the power output of synchronous machines varies with respect to their rotor angle changes. Under steady state condition there is equilibrium in between input mechanical torque and output electromagnetic torque. When system faces disturbances this equilibrium upset resulting in acceleration or deceleration of the rotors of machine. If one generator temporarily runs faster as comparison to other one, the angular position of its rotor relative to that of slower machine will advance. The resulting angular difference transfers part of load from slow machine to fast machine. This tends to reduce the speed difference and angular separation. If system not able to absorb kinetic energy corresponding to their rotor speed difference than instability occurs .For any given situation stability of system depends whether deviation in angular position of rotor provides sufficient restoring torque or not. The change in electromagnetic torque is resolved in two components [31] [32]:

1) Synchronizing torque component, in phase with rotor angle deviation

2) Damping torque component, in phase with speed deviation

System stability requires existence of both components of torque for each synchronous machine. Non oscillatory instability occurs when sufficient synchronizing torque is missing while oscillatory instability occurs due to lack of sufficient damping torque. Rotor angle stability is further classified as:

1) Small disturbance rotor angle stability

2) Transient Stability

2.2.1 **Small disturbance rotor angle stability**: It depends upon initial operating state of the system. Mainly small disturbance rotor angle stability problem associated with insufficient damping of oscillations.

2.2.2 **Transient stability:** Transient stability is mainly concerned with the ability of power system to maintain synchronism when subjected to severe disturbances such as three phase fault on transmission line. It's not only depends upon on the operating state of system but also on the severity of disturbance [31] [32].

2.3 Power – Angle Curve

The graphical representation of power Pe and the load angle δ is called the power angle diagram or power-angle curve. Maximum power is transferred when δ=90^0. δ increased beyond 90^0 as P_e decreases and becomes zero at 180^0

2.4 Power Angle Equation

The expression establishing the relationship between the active power transferred (P_e) to the system and angle δ is known as proper angle equation. The expression for the active power transferred to the system is given by

$$P = \frac{EV}{X} \sin \delta \tag{2.1}$$

Where

$$X = X_d + X_1 \tag{2.2}$$

X	Transfer reactance
X_d	Transient reactance of the machine
X_1	Reactance of transmission line
E	Magnitude of the voltage behind direct axis synchronous reactance of the machine
V	Voltage of infinite bus
δ	Angle between the voltage E and V

The maximum steady state power transfer occurs when δ =90^0. From equation

$$P_{e\,max} = \frac{EV}{X} \sin 90 = \frac{EV}{X} \tag{2.3}$$

$$P_e = P_{e\,max} \sin \delta \tag{2.4}$$

2.5 Swing Equation

The equation establishing the relationship between the accelerating power and angular acceleration is called swing equation. It is a non-linear differential equation of the second order.

$$M\frac{d^2a}{dt^2} = P_s - P_e = P_a \quad (2.5)$$

$$M = J\omega \quad (2.6)$$

Where

M	Angular momentum of the rotor
J	Moment of inertia of the rotor
ω	Synchronous speed of the rotor
P_s	Mechanical power input
P_e	Electrical power output
P_a	Accelerating power

2.6 Equal Area Criteria

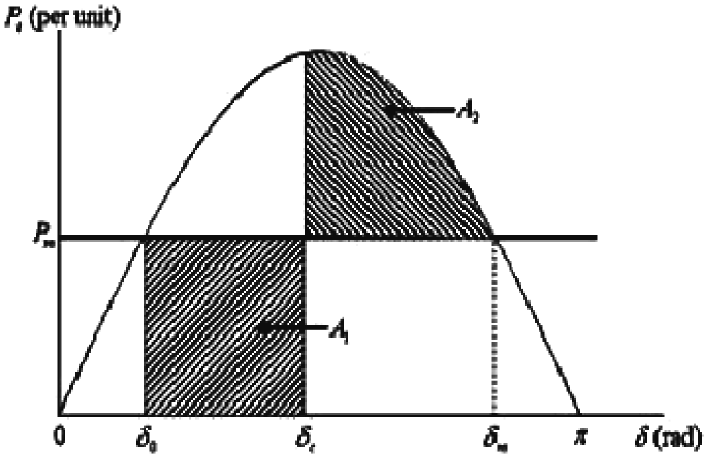

Figure 2.2 Power-Angle curve [31]

Consider the power angle curve as shown in Figure 2.2. Suppose the given system is operating at an angle of δ_0 and delivering a power of P_m when fault occurs. During fault transmitted electrical power decreases significantly while mechanical power i.e. Pm remains constant, the accelerating power P_a becomes equal to P_m. The difference in the power develops the rate of change of stored kinetic energy in to rotor masses. As a result the rotor will accelerate due to affect of accelerating power and hence the load angle will increase. Now at angle δ_c suppose the circuit breaker recloses. Thus power will then revert back to the normal operating curve. At that point the transmitted electrical power will be exceed than the mechanical power and machine will start to decelerate. However, due to stored kinetic energy in machine, the load angle will still keep on increasing. If this increasing angle will not stop than system will loss synchronism and become unstable. The relationship between the rotor angle and the accelerating power [31]:

$$\frac{d^2\delta}{dt^2} = \frac{\omega_0}{2H}(P_m - P_e) \tag{2.7}$$

Multiply both sides by $2\frac{d\delta}{dt}$ than equation [1] becomes

$$2\frac{d\delta}{dt}\frac{d^2\delta}{dt^2} = \frac{\omega_0(P_m - P_e)}{H}\frac{d\delta}{dt} \tag{2.8}$$

After rearranging equation 2 we get

$$\frac{d}{dt}\left[\frac{d\delta}{dt}\right]^2 = \frac{\omega_0(P_m - P_e)}{H}\frac{d\delta}{dt} \tag{2.9}$$

Now integrate equation between two arbitrary angles δ_0 and δ_c becomes

$$\frac{H}{\omega_0}\left[\frac{d\delta}{dt}\right]^2 = \int_{\delta_0}^{\delta_c}(P_m - P_e)\, d\delta \tag{2.10}$$

Now suppose the generator is at rest at δ_0. We then have $\frac{d\delta}{dt}$ = 0. Once a fault occurs, the machine starts accelerating. Once the fault is cleared, the machine keeps on accelerating before it reaches its peak at δ_c , at which point we have again $\frac{d\delta}{dt} = 0$ Thus area of accelerating is given as

$$A_1 = \int_{\delta_o}^{\delta_c}(P_m - P_e)d\delta = 0 \tag{2.11}$$

Similarly area of deceleration is given as

$$A_2 = \int_{\delta_c}^{\delta_m}(P_e - P_m)d\delta = 0 \tag{2.12}$$

Case 1:

If area of acceleration is greater than area of deceleration i.e. $A_1 > A_2$. The generator load angle will then cross the pointδ_m, beyond which the electrical power will be less than the mechanical power forcing the acceleration power to be positive. The generator will therefore start accelerating before it slows down completely and will eventually become unstable.

Case 2:

If area of acceleration is lesser than area of deceleration i.e. $A_1 < A_2$. The machine will decelerate completely before accelerating again. The rotor inertia will force the subsequent acceleration and deceleration areas to be smaller than the first ones of the machine will eventually attain the steady state.

Case 3:

If the area $A_1 = A_2$, then the accelerating area is equal to decelerating area and this defines the boundary of the stability limit.

2.7 Swing Curve

When the swing equation is solved we obtain the expression for power angle as a function of time. A graph of solution is called swing curve of the machine and inspection of the swing curve of all machine of the system will show whether the machine remain in synchronism after a disturbance or not. If δ increases continuously with time the system is unstable. While if δ starts decreasing after reaching a maximum value it is inferred that the system will remain stable.

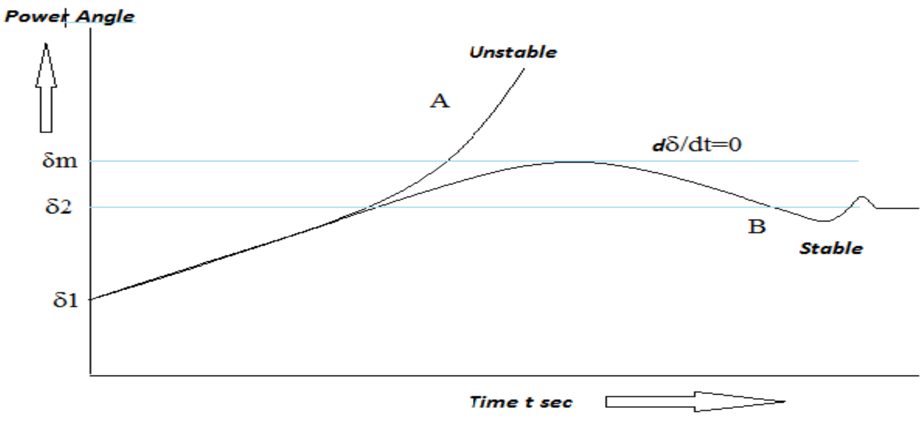

Figure 2.3 Swing Curve

Chapter 3

DESIGN OF STATCOM CONTROLLERS

3.1 Fuzzy Logic Controller

3.1.1 Introduction

Fuzzy Logic was proposed in 1965 by Lofti A. Zadeh of the University of California at Berkeley in 1965. Fuzzy logic gained popularity by Seiji Yasunobu and Soji Miyamoto of Hitachi who provided a simulation that proves the superiority of fuzzy control system for the Sendai Railway [44]. Basically Fuzzy logic is mathematical tool for dealing with uncertainty and it provides an inference structure that enables appropriate human reasoning capabilities The utility of fuzzy system lies in their ability to model uncertain or ambiguous data. There is relationship between complexity and fuzzy. As complexity of a task increases it becomes necessity that system should be fuzzy in nature [35]. It can be said that Fuzzy logic is an extended version of Boolean logic because Fuzzy logic deals with uncertain and imprecise knowledge while in classical Boolean logic truth there is no provision for approximate reasoning [33].

Table 3.1: Boolean and Fuzzy logic-- A Comparison [33].

	Classical Boolean logic	Fuzzy Logic
Inventor	George Boole	Lofti Zadeh
Truth	Can have two values : True (1) , False(0) Example P(small(Sandy)) = 1 It means that the proposition that Sandy is small. There is no intermediate state between 1 and 0. Sandy is small can be true or false.	$0 \leq \mu \leq 1$ Example P(small(Sandy)) = 0.7 It means that the proposition that Sandy is small is seventy percent true. One can assign the various linguistic values to the truth. For example truth , very truth and so on
Predicates	Crisp(greater than, etc)	Rich, ill, much etc
Probabilities	Numerical or interval value	Numerical or interval plus linguistic such as likely, unlikely etc

3.1.2 Why Fuzzy Logic in Power System

Traditionally in power system operations analytical approaches have been used over the years. These analytical approaches based on the mathematical formulation which is derived by using assumptions but the results obtained for large scale power system operations from these analytical approaches are not trivial. Moreover there are many uncertainties in power system operation because of its complexity, geography and influence of unexpected events. The recently deregulation of power utilities has introduced new issues into the existing problems. This all facts make it difficult to deal with many power systems problems using mathematical formulations alone [34]. Fuzzy logic is only powerful technique which can handle these problems because:

- Fuzzy has rule based operation therefore it can process any number of reasonable inputs and outputs.
- Because of its rule based operation nonlinear systems can be controlled which is difficult to model mathematically.
- Fuzzy logic reduces the time needed to develop the complex systems.

3.1.3 How is FL used?

- Determine the control objectives and criteria: A clear understanding that when system is to be control? What parameters need to be controlled and what kind of response required? What are the possible system failure modes?
- Derive relationship between input and output variables and choose minimum number of inputs to fuzzy logic engine (typically error and rate-of-change-of-error).
- The control problem is break down into a series of (IF X AND Y THEN Z) rules that define the desired system output response for given system input conditions by using the rule based structure of fuzzy logic. Number of input parameters that are to be processed and number of fuzzy variables associated with each parameter determines the complexity and number of rules. If possible, use at least one variable and its time derivative. Although it is possible to use a single, instantaneous error parameter without knowing its rate of change, this cripples the system's ability to minimize overshoot for a step inputs.
- Create FL membership functions that define the meaning (values) of Input / Output terms used in the rules.

- Test the system, evaluate the results, tune the rules and membership functions, and retest until satisfactory results are obtained.

3.1.4 Linguistic Variable

Fuzzy Logic is mainly concern with quantifying and reasoning of vague or fuzzy terms. These fuzzy terms are referred as linguistic variables. For example in the statement ‘the condition of the power system is stable’, the condition is a linguistic variable and its value is stable. The range of possible values of linguistic variables known as the universe of discourse [34].

3.1.5 Membership Function

Designing membership function is an important issue in fuzzy sets proposed by Zadeh in 1965. Selection of appropriate membership function is critical because output of fuzzy systems can be changed by changing the parameters of membership function. A membership function can be define as a curve that defines how each point in the input space is mapped to a membership value. Membership function can build from several basic functions: piecewise linear function, Gaussian distribution function, sigmoid curve and quadratic and cubic polynomial curves.

3.1.5.1 Shape – The various shapes of membership functions are triangular, bell, trapezoidal, Gaussian, gauss2mf etc. More complex functions are possible but require greater computing overhead to implement. HEIGHT or magnitude (usually normalized to 1) WIDTH (of the base of function), SHOULDERING (locks height at maximum if an outer function. Shouldered functions evaluate as 1.0 past their center) CENTER points (center of the member function shape) OVERLAP (N&Z, Z&P, typically about 50% of width but can be less).

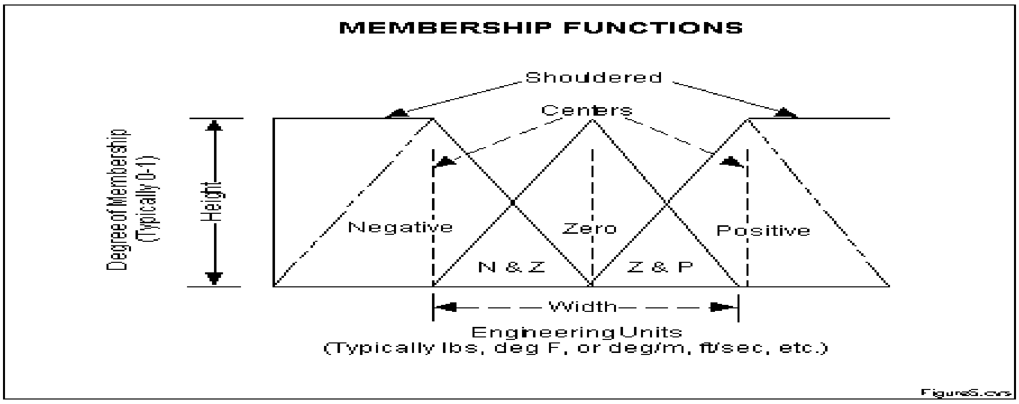

Figure 3.1 Membership functions

3.1.6. Design of Fuzzy Logic Controller:

Fuzzy Logic Controller is mainly comprises of four principal components:

1) Fuzzification

2) Fuzzy rule Base

3) Fuzzy inference

4) Defuzzification

Graphically it can be represented as

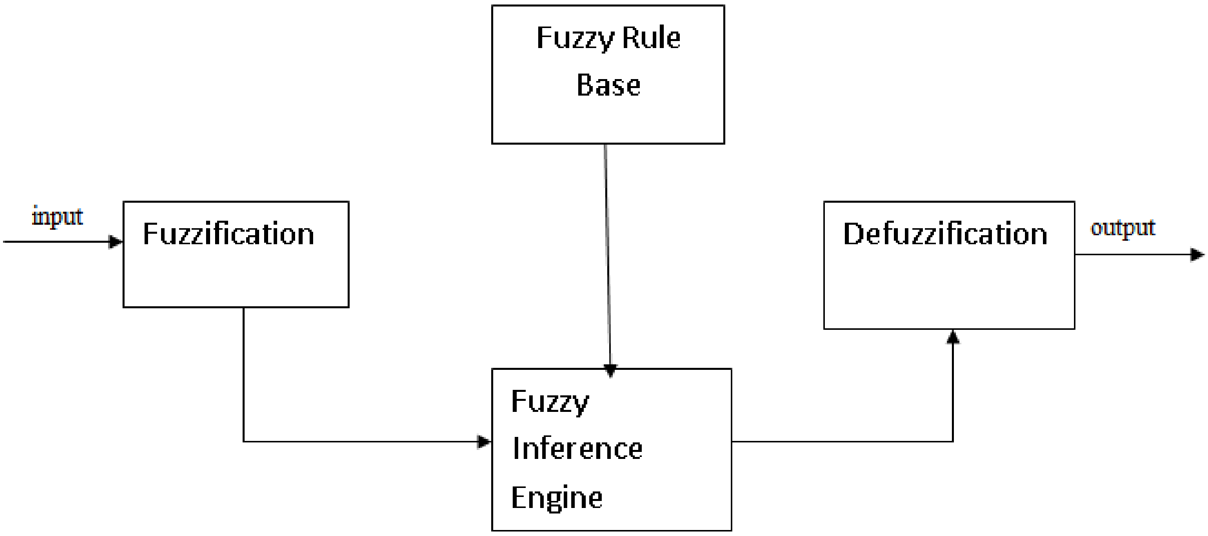

Figure 3.2 A Fuzzy System [35]

3.1.6.1 Fuzzification: Fuzzification is the process where the crisp quantities are converted to fuzzy. Broadly functions of fuzzification classified as:

- Determine the value of input variables.
- Scale Mapping technique i.e. converts the range of input variables values into corresponding universe of discourse.
- Fuzzification i.e. converts input data into suitable linguistic value which may be viewed as labels of fuzzy sets [34].

In any practical applications, in industry etc, measurement of voltage, current, temperature etc. There might be a negligible error. This causes imprecision in the data. The imprecision can be represented by the membership functions. Hence fuzzification is performed [35].

3.1.6.2 Fuzzy Rule Base: Fuzzy system consists of expert knowledge based set of linguistic statements. The Knowledge base included the knowledge of the system on which fuzzy rules need to be applied and the attendant control gains. It consists of a “data base” and a “rule base”:

- The data base includes necessary definitions that are required to define linguistic control rules and fuzzy data manipulation in an FLC.
- The rule base characterizes the control goals and control policy of the domain experts by means of a set of linguistic control rules [34].

The syntax that is used to express these rules is: if <*fuzzy proposition*>, then <f*uzzy* proposition >, where the fuzzy propositions are of the form, ‘*x is Y’ or ‘x is not Y’*

3.1.6.3 Fuzzy Inference: Fuzzy inference is the core of a fuzzy logic controller, its main function is to simulate human decisions based on fuzzy concepts and of determine fuzzy control actions by applying the rules of inference in fuzzy logic. In Inference engine, fuzzy ‘IF-THEN’ rules from fuzzy rule base is used to map fuzzy input sets to fuzzy output sets.

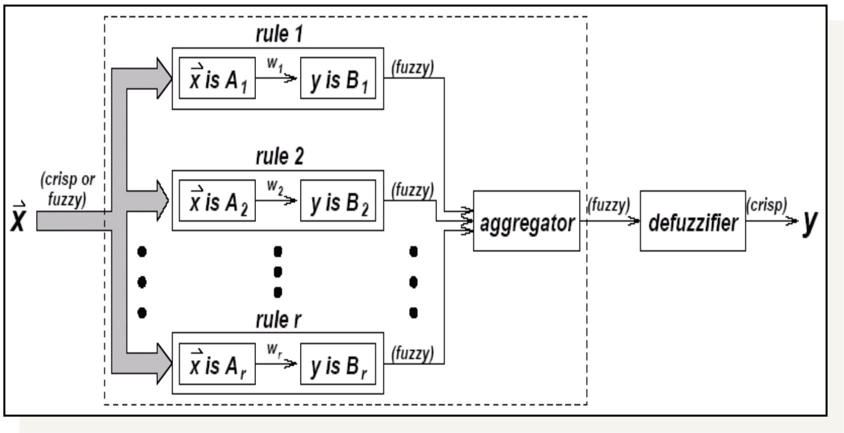

Figure 3.3 Block diagram of Fuzzy Inference System [41]

3.1.6.4 Defuzzification: The defuzzification performs the following functions:

- Scale Mapping i.e. converts the range of values of output variables into corresponding universe of discourse.
- Defuzzification i.e. performs a non fuzzy control action from an inferred fuzzy control action [34].

The various defuzzification methods are:

- Max-Membership principle

- Centroid Method
- Weighted average Method
- Mean-max membership
- Centre of sums
- Centre of largest area
- First of maxima or last of maxima

In this thesis Centroid method is used

Centroid Method: This defuzzifier determines the centre of gravity of the fuzzy control space and uses this value as the output of the fuzzy logic system. The resultant output is sensitive to all rules executed . The centroid defuzzifier is the most commonly used method.

3.1.7 Fuzzy Inference Methods:

Fuzzy inference methods can be classified as

- Mamdani's method
- Takagi and Sugeno's method
- Tsukamoto method

In this thesis work Mamdani style of inference is used.

3.1.7.1 Mamdani Method: Mamdani Method proposed in 1975 as an attempt to control a steam engine and boiler combination by synthesizing a set of linguistic control rules obtained from experienced human operators. This method can be understand by considering two-rule system each rule consists of two inputs (antecedents) and one output (consequent) . x_1 and x_2 considered to be an input while y is considered to be an output of fuzzy system which is described by a collection of r linguistic IF-THAN propositions in the mamdani form:

$$IF\ x_1\ is\ A_1^k\quad and\ x_2\ is\ A_2^k\ THEN\ y^k\ is\ B^k\quad for\ \ k = 1,2,\ldots,r \qquad (3.1)$$

Where A_1^k and A_1^k are the fuzzy sets representing the kth antecedents pairs and B^k is the fuzzy set representing the kth consequent. Membership for the inputs x_1 and x_2 will be described by

$$\mu(x_1) = \delta\big(x_1 - input(i)\big) = \begin{cases} 1, & x_1 = input(i) \\ 0, otherwise \end{cases} \qquad (3.2)$$

$$\mu(x_2) = \delta(x_2 - input(j)) = \begin{cases} 1, & x_2 = input(j) \\ 0, & otherwise \end{cases} \quad (3.3)$$

Based on the Mamdani implication method of inference the aggregated output for the rules r

Will be given:

$$\mu_B(y) = \max\left[min\left[\mu_{A_1^k}(input(i)), \mu_{A_{21}^k}(input(j))\right]\right] \quad k = 1,2,\ldots\ldots,r \quad (3.4)$$

The above equation graphical interpretation is represented in Figure 3.4

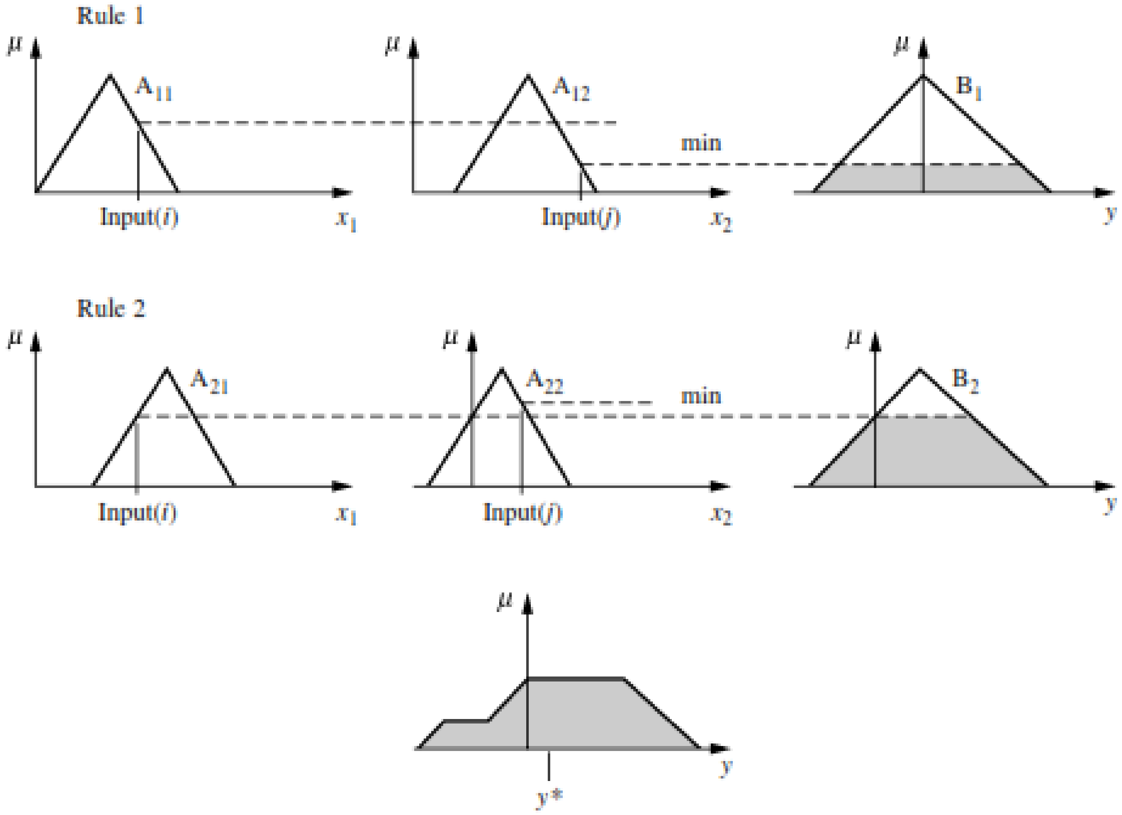

Figure 3.4 Mamdani (max – min) inference method with crisp inputs [36]

In Figure 3.4, A_{11} and A_{12} represents two inputs of Rule 1 while B_1 represents output of Rule 1 in similar way A_{21} and A_{22} represents inputs of Rule 1 and B_2 represents output of Rule 2 [36].

3.1.8. Steps for Building a Fuzzy Logic Controller

- Determine the values of input and output variables.
- Get control knowledge by data analysis.

- Assign membership functions for input and output fuzzy variables.
- Determine fuzzy rules.
- Tune membership functions and rules by varying the scale of membership functions and rules.

Repeat steps 1 to 5 until the desired performance obtained [37].

3.1.9 Design of Fuzzy based Controller for STATCOM

Here fuzzy controller is designed with two inputs i.e. generator frequency and its derivative and a single output i.e. Alpha. The advantage of this controller is that it doesn't required detailed information about the system. Mamdani Fuzzy Model is use for the purposed fuzzy controller and "if-Then" rules use for inference engine. There is fuzzy variable corresponding to each controller input and these inputs are fuzzified by using membership function and crisp output is calculated using Center of area (COA) method. Proper membership functions are defined for output variables too [38].

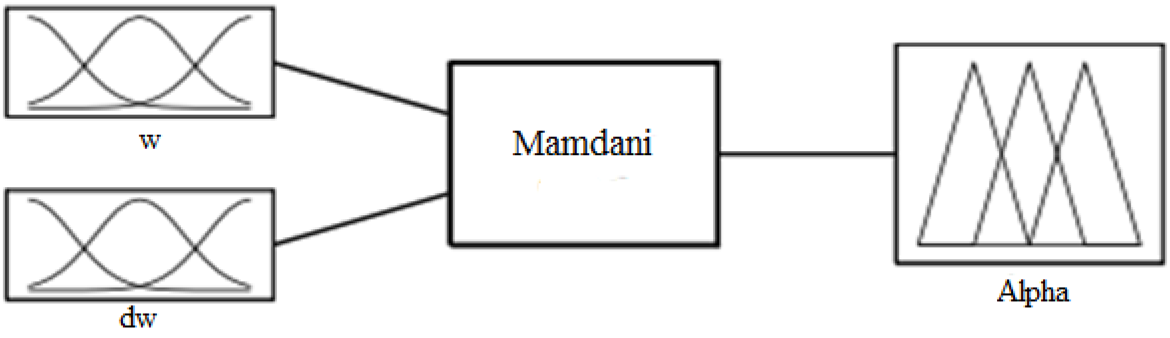

Figure. 3.5 Two input single output FLC

Membership functions for input variables i.e. ω and its derivative $\frac{d\omega}{dt}$ is given in Figure3.6 & Figure 3.7

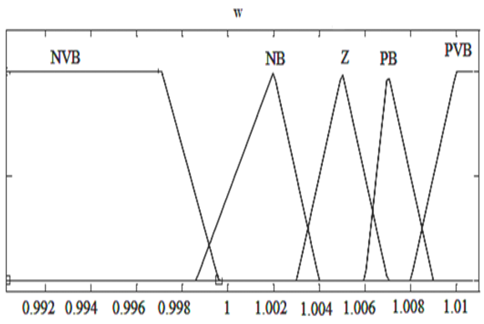

Figure.3.6 input membership function of ω

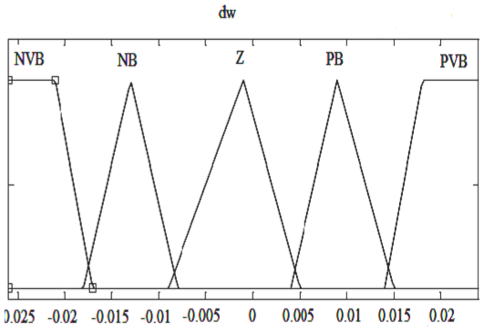

Figure. 3.7 input membership function of $\frac{dw}{dt}$

The proper range for each term and the number of membership functions can be defined based on designer experiments and the system configuration. Membership functions of dω/dt are symmetrical but those of ω are defined in different way. It is because of the behaviour of machine speed and can be known by simulation results. Fig 3.8 shows the output membership functions of alpha angle of voltage source converter which is used to build controller crisp output from the fuzzy outputs of inference engine. The deffuzzification method used for this purpose is COA [38].

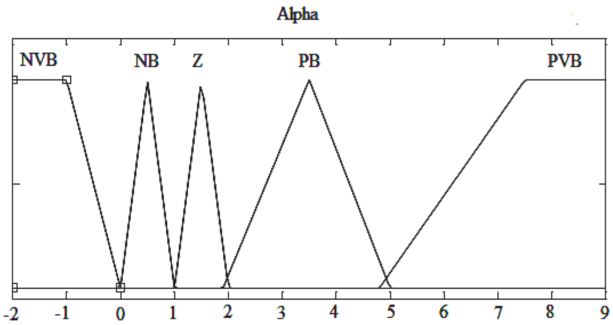

Figure.3.8 Output membership function α

Rule based table on which fuzzy controller for STATCOM installed on two machine systems is designed as given.

Table 3.2: Fuzzy Rules

ω dω/dt	NVB	NB	Z	PB	PVB
NVB	nb	nb	nb	nb	nb
NB	nb	nb	nb	nb	nb
Z	nb	nb	z	pb	pb
PB	pb	pb	pb	pb	pb
PVB	pb	pb	pb	pb	pb

The logic behind rule can be easily derived. For example

R1: if ω is ***positive big*** and dω is ***positive very big*** than firing angle α is positive big.

R2: if ω is ***positive big*** and dω is ***positive big*** than firing angle α is positive big.

The logic is that when frequency is high and it's rising fast,the system is in critical condition because the input mechanical power of generators is more than output electrical power. Therefore the STATCOM should inject big capacitive current into the network hence alpha should be small [38]. By this action the transmittable power capacity of the line which

STATCOM installed will be increased and the transient stability will be improved. Other conditions can be analysed in a similar way.

3.2. Fuzzy- PI Controller

3.2.1 Introduction

Proportional-Integral Controller is one of the most commonly used controllers in Industries. This proportional-Integral Controller is mostly referred as PI Controller in industry where P referred to proportional term while I referred to integral term. The proportional function is to adjusts controller output according to the size of error while function of integral is to eliminates the steady state offset. A General arrangement of PI Controller in matlab under continuous and discrete mode as shown in Figure 3.9 and Figure 3.10

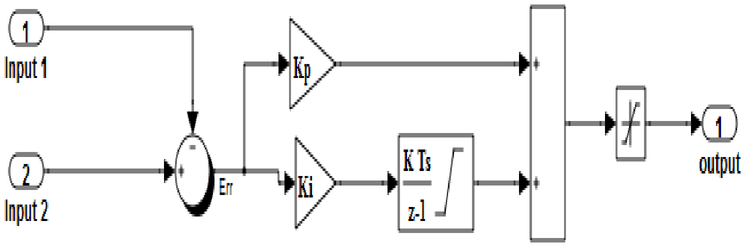

Figure. 3.9 PI Controller in discrete mode

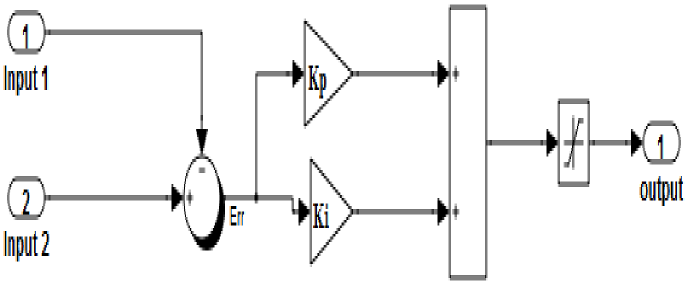

Figure.3.10 PI Controller in Continuous mode

3.2.2 Need of Fuzzy-PI controller:

In large power plants more than one PI controller are used. Traditionally these PI controllers are tuned with constant parameters which are not robust enough when there is change in design parameters. In order to overcome this problem different methods are proposed. Fuzzy-PI Controller is one of them.

3.2.3 Design of Fuzzy-PI controller for STATCOM:

In order to improve the transient stability of power system two fuzzy-PI controllers have been designed to separately regulate the voltage and current. For voltage regulator the difference between V_{meas} and V_{ref} i.e. error and its derivative are taken as input for fuzzy adjuster similarly for current regulator difference between I_q and I_{q_ref} and its derivative are taken as input for fuzzy adjuster. This fuzzy adjuster is used to adjust the parameters of proportional gain K_p and integral gain K_i .

$$\begin{cases} K_p = K_p^* + \Delta K_p \\ K_i \;= K_i^* + \Delta K_i \end{cases} \tag{3.5}$$

Where K_p^* and K_i^* are the reference values of fuzzy-PI based controllers [39]. The general arrangement of fuzzy-PI controller in Voltage Regulator and Current Regulator as given in Figure 3.11 & Figure 3.12

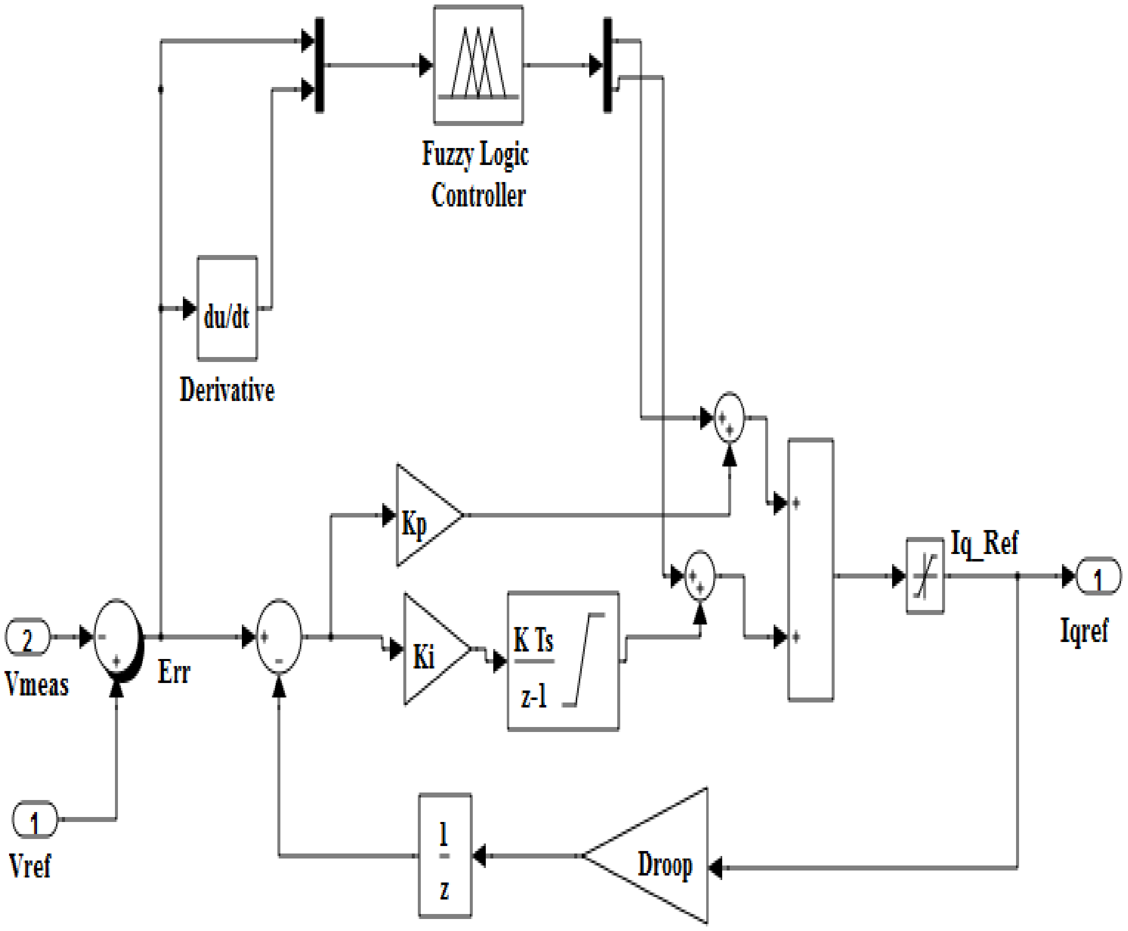

Figure 3.11 Fuzzy-PI arrangement for Voltage Regulator

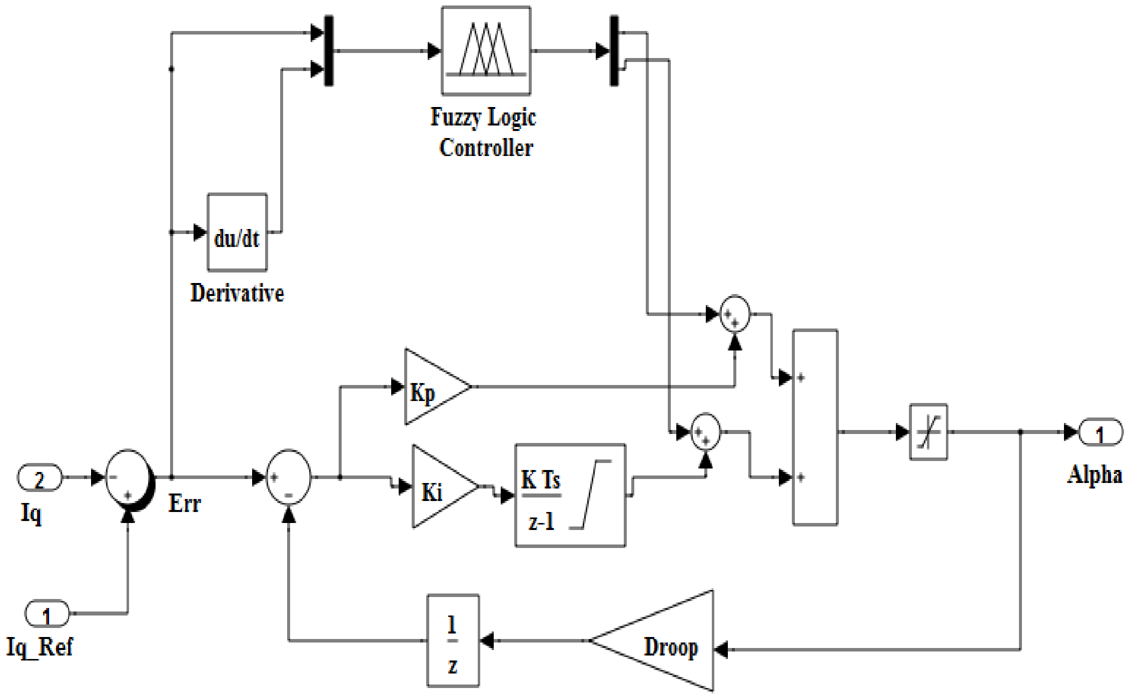

Figure 3.12 Fuzzy-PI arrangement for current Regulator

The error and change of error are used as numerical value from the real system. Five fuzzy sets i.e. NVB (negative very big), NB (negative big), Z (Zero), PB (Positive big), PVB (Positive very big) are chosen to convert this numerical values into linguistic variables. The membership functions of input and output variables of voltage regulator and current regulator are given in Figure 3.13 to Figure 3.20

Voltage Regulator

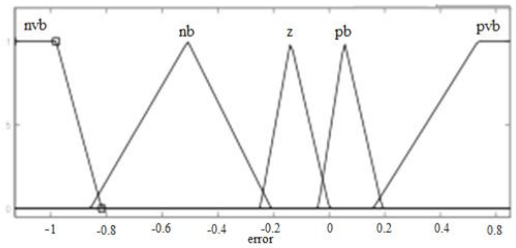

Figure 3.13 input membership function of error

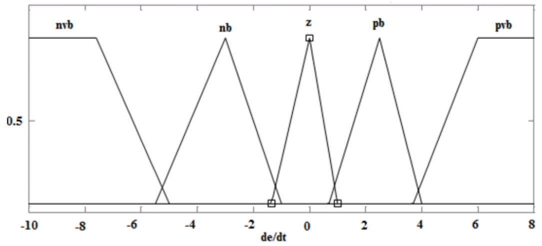

Figure 3.14 input membership function of $\frac{de}{dt}$

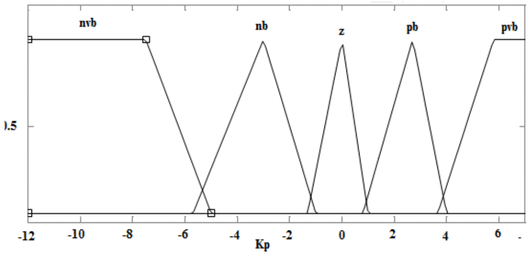

Figure 3.15 output membership function of K_p

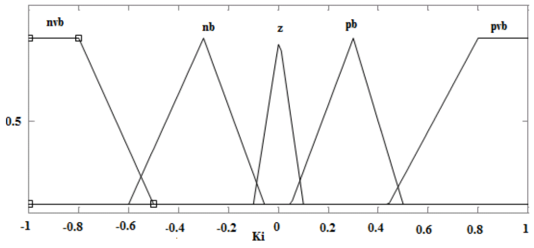

Figure 3.16 output membership function of K_i

Current Regulator

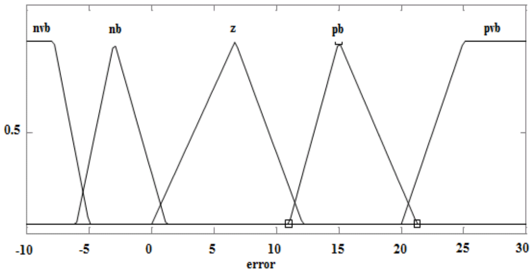

Figure 3.17 Input membership function of error

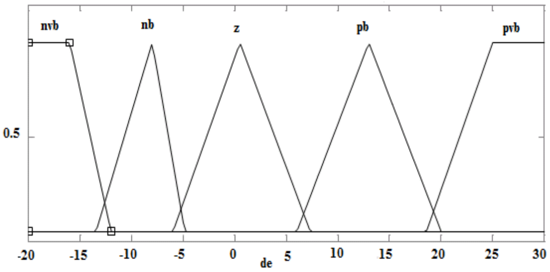

Figure 3.18 Input membership function of de/dt

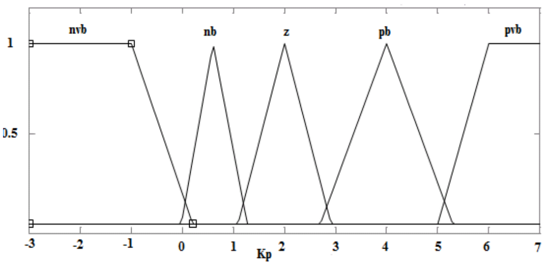

Figure 3.19 Input membership function of K_p

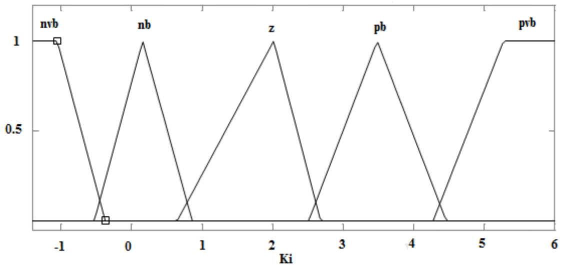

Figure 3.20 Input membership function of K_i

Rule based table on which Fuzzy-PI controller for STATCOM installed on two machine systems is designed as given

Table 3.3: Rule Table for K_p

e de/dt	NVB	NB	Z	PB	PVB
NVB	nb	nb	nb	pb	z
NB	nb	nb	z	z	pb
Z	nb	nb	z	pb	pb
PB	nb	nb	z	pb	pb
PVB	z	nb	pb	pb	pb

Table 3.4: Rule Table for K_i

e de/dt	NVB	NB	Z	PB	PVB
NVB	z	nb	nb	nb	z
NB	z	nb	nb	z	z
Z	z	z	z	pb	z
PB	z	z	pb	pb	z
PVB	z	pb	pb	pb	z

The fuzzy Rules are determined from practical experience and simulations in order to obtain maximum performance for the system. Following facts are considered for deriving rules for K_p and K_i

1) For Large values of e and de/dt a large ΔK_p is required.
2) For very large values of e and de/dt, ΔK_i is set to zero in order to avoid control saturation and ΔK_i is considered to be large for small values of e (error) in order to reduce steady state error [39].

.3.3 ANFIS based STATCOM controller

3.3.1 Introduction

In modern industrial applications fuzzy systems become popular because it implements human reasoning that can be programmed into fuzzy logic language i.e. membership functions, rules etc [40] but designing a fuzzy system is not an easy task because the good performance of fuzzy system depends upon the accuracy of membership function and rules. Determining appropriate membership functions and rules are major constraints in fuzzy systems [34]. These constraints of fuzzy systems lead to development of ANFIS which stands for Adaptive Neuro - based fuzzy inference system. ANFIS contains the advantages of both ANN and FL. It is applied the learning algorithm on the FL parameters to determine the optimal solution and to minimize the error. In this thesis hybrid Learning Algorithm is used to determine the optimal solution and minimizing the error.

3.3.2 ANFIS Architecture

Figure 3.21 shows the Sugeno-fuzzy model based ANFIS Architecture having two inputs i.e.u_1 and u_2 and one output i.e. y. On the basis of functions of nodes it can be grouped it into five Layers

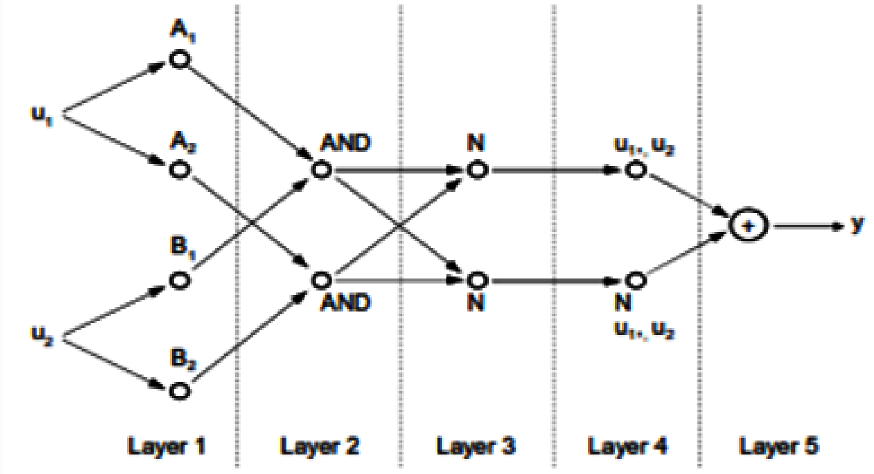

Figure.3.21 Basic ANFIS Architecture [41]

Layer 1: Every node i in this layer is an adaptive node with a node function

$$O_{1,i} = \mu_{A_i}(u_1), \qquad for\ i = 1,2, or \tag{3.6}$$

$$O_{1,i} = \mu_{B_{i-2}}(u_2), \qquad for\ i = 3,4, \tag{3.7}$$

Where u_1 or u_2 is the input to node i and A_i or B_{i-2} is a linguistic label associated with this node. $O_{1,i}$ is the membership grade of a fuzzy set $A(= A_1, A_2, B_1, B_2)$ and it specifies the degree to which the given input $u_1\ (or\ u_2)$ satisfies the quantifier$A$. The membership function for A can be any appropriate parameterized membership function. Generally bell membership function is used.

Layer 2:

Here output of each node represents the firing strength of a rule and it's given as the product of all the incoming signals:

$$O_{2,i} = w_i = \mu_A(u_1x)\mu_B(u_2), i = 1,2 \tag{3.8}$$

Layer 3:

In this Layer, The ith node calculates the ratio of the ith rule's firing strength to the sum of all rules' firing strengths:

$$O_{3,i} = \overline{w_i} = \frac{w_i}{w_1+w_2} \tag{3.9}$$

Output of this layer referred as normalized firing strengths.

Layer 4:

The Parameters of the nodes in this layer are called consequent parameters and node function of every i_{th} node of this layer is:

$$O_{4,i} = \overline{w_i}f_i = \overline{w_i}(p_iu_1 + q_iu_2 + r_i \tag{3.10}$$

Where $\overline{w_i}$ is a normalized firing strength from layer 3 and $\{p_ix + q_iy + r_i\}$ is the parameter set of this node

Layer 5:

Nodes in this Layer are fixed and sum all incoming signals [41]:

$$O_{5,i} = \sum_i \overline{w_i}f_i = \frac{\sum_i w_i f_i}{\sum_i w_i} \tag{3.11}$$

3.3.3 Hybrid Learning Algorithm

From the ANFIS architecture it's observed that when the values of premise parameters are fixed, the overall output can be expressed as a linear combination of the consequent parameters. Let us consider the total parameter set as:

$$S = S_1 + S_2 \tag{3.12}$$

Where

S is set of total parameters

S_1 is set of premise (non-linear) parameters

S_2 is set of consequent (linear) parameters

So, ANFIS uses a two pass learning algorithm:

- Forward Pass. Here S_1 is unmodified and S_2 is computed using a LSE algorithm.
- Backward Pass. Here S_2 is unmodified and S_1 is computed using a gradient descent algorithm.

So, the hybrid learning algorithm uses a combination of steepest descent and least squares to adapt the parameters in the adaptive network [41].

3.3.4 Design of ANFIS based STATCOM controller

The membership functions for input and output variables and rule table for ANFIS that is obtained by hybrid learning algorithm are shown in Figure 3.22, Figure 3.23 & Figure 3.24

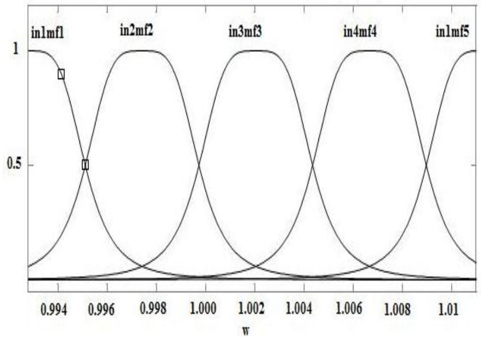

Figure 3.22 Input variable ω

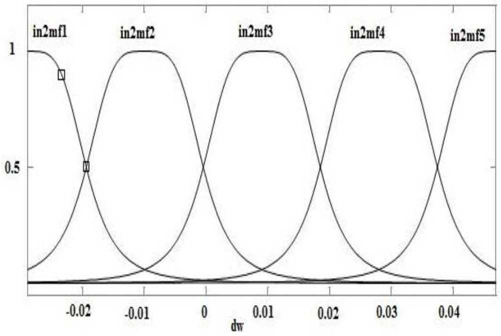

Figure 3.23 Input variables $\frac{d\omega}{\mathrm{dt}}$

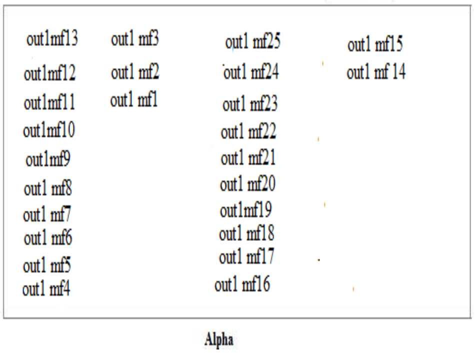

Figure 3.24 Output variable α of VSC

Table 3.5: Hybrid learning algorithm based rule table

ω dω/dt	mf1	mf2	mf3	mf4	mf5
mf1	mf1	mf6	mf 11	mf 16	mf 21
mf2	mf2	mf7	mf 12	mf 17	mf 22
mf3	mf3	mf 8	mf 13	mf 18	mf 23
mf4	mf4	mf 9	mf 14	mf 19	mf 24
mf5	mf5	mf 10	mf 15	mf 20	mf25

CHAPTER – 4

RESULTS AND DISCUSSION

4.1 Two Machine Systems

Figure 4.1 shows single line diagram of two area system (area 1 & area 2). Area1 (1000 MW hydraulic generation plant) connected to Area 2 (5000 MW hydraulic generation Plant.) through 500 kV, 700 km transmission line.

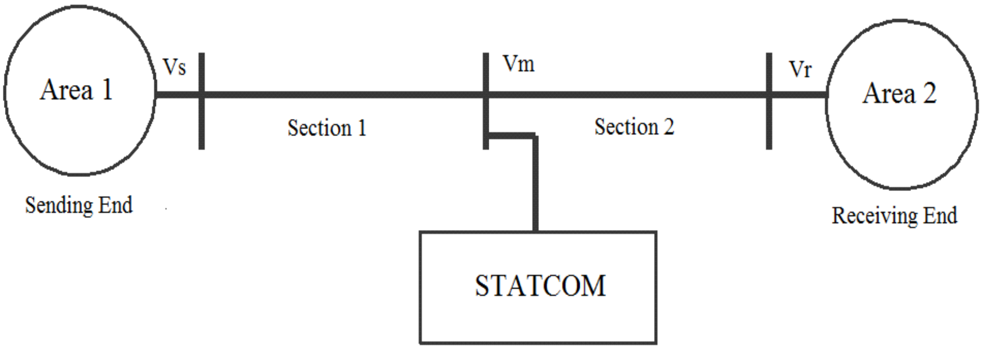

Figure 4.1 Single Line Diagram of Two Area Interconnected System

Both plants fed to a load centre, modelled by a 5000 MW resistive load. System is initialized so that line carries 950 MW which is close to its surge impedance loading. In order to maintain system stability Static synchronous compensator of 200 MVA is connected at midpoint of transmission line. By connecting it at midpoint the power transfers capability of system increases significantly [42] [43].

4.2. Simulation Model of Two Machine System

Simulink Model of two machines (M1 & M2) system installed with Fuzzy, Fuzzy-PI and ANFIS based STATCOM controllers are shown in Figure 4.2, Figure 4.3 and Figure 4.4. Machine M1 referred to a 1000 MW hydraulic generation plant while Machine M2 referred to 5000 MW generating plant. Each machine equipped with a Governor, excitation system and Power system stabilizer. These components are included in Turbine & Regulator1 and Turbine & Regulator 2. Both machine connected through a 500 kv, 700km transmission line. Resistive load of 5000MW connected on Machine M2 side. GTO based STATCOM having rating of 200 MVA connected at midpoint of transmission line.

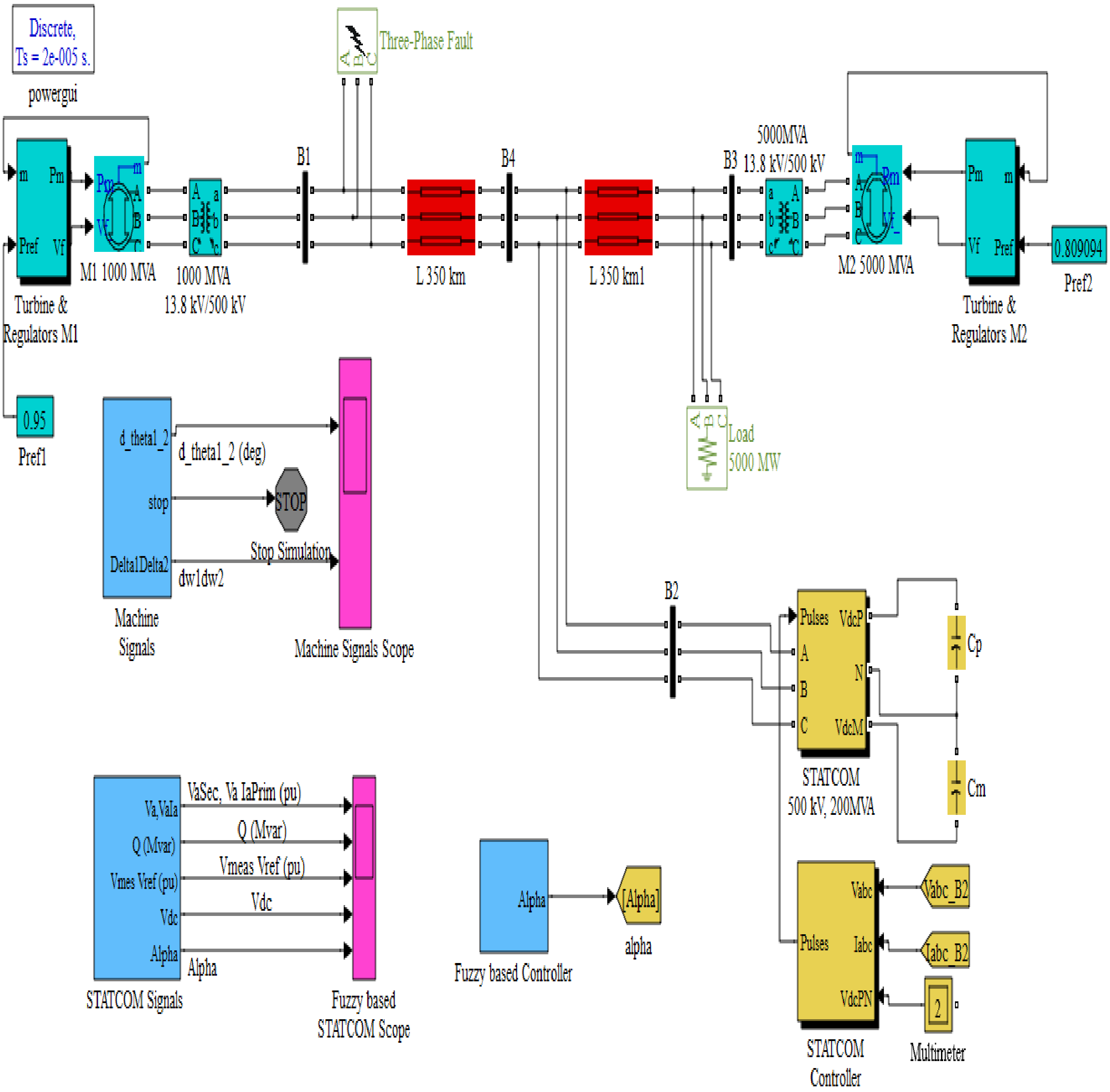

Figure 4.2 Two machine system installed with Fuzzy Based STATCOM Controller

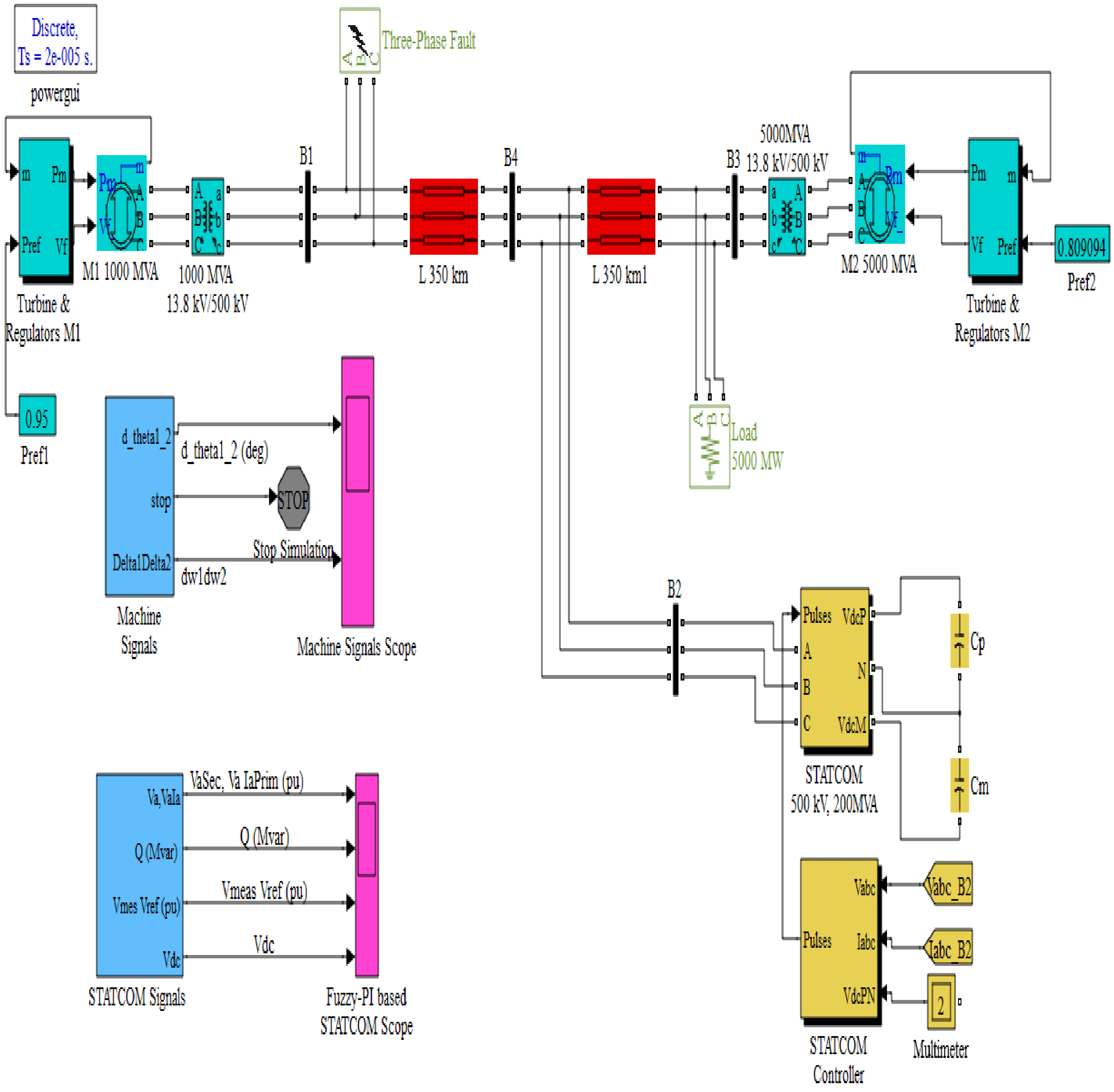

Figure 4.3 Two machine system installed with Fuzzy-PI Based STATCOM Controller

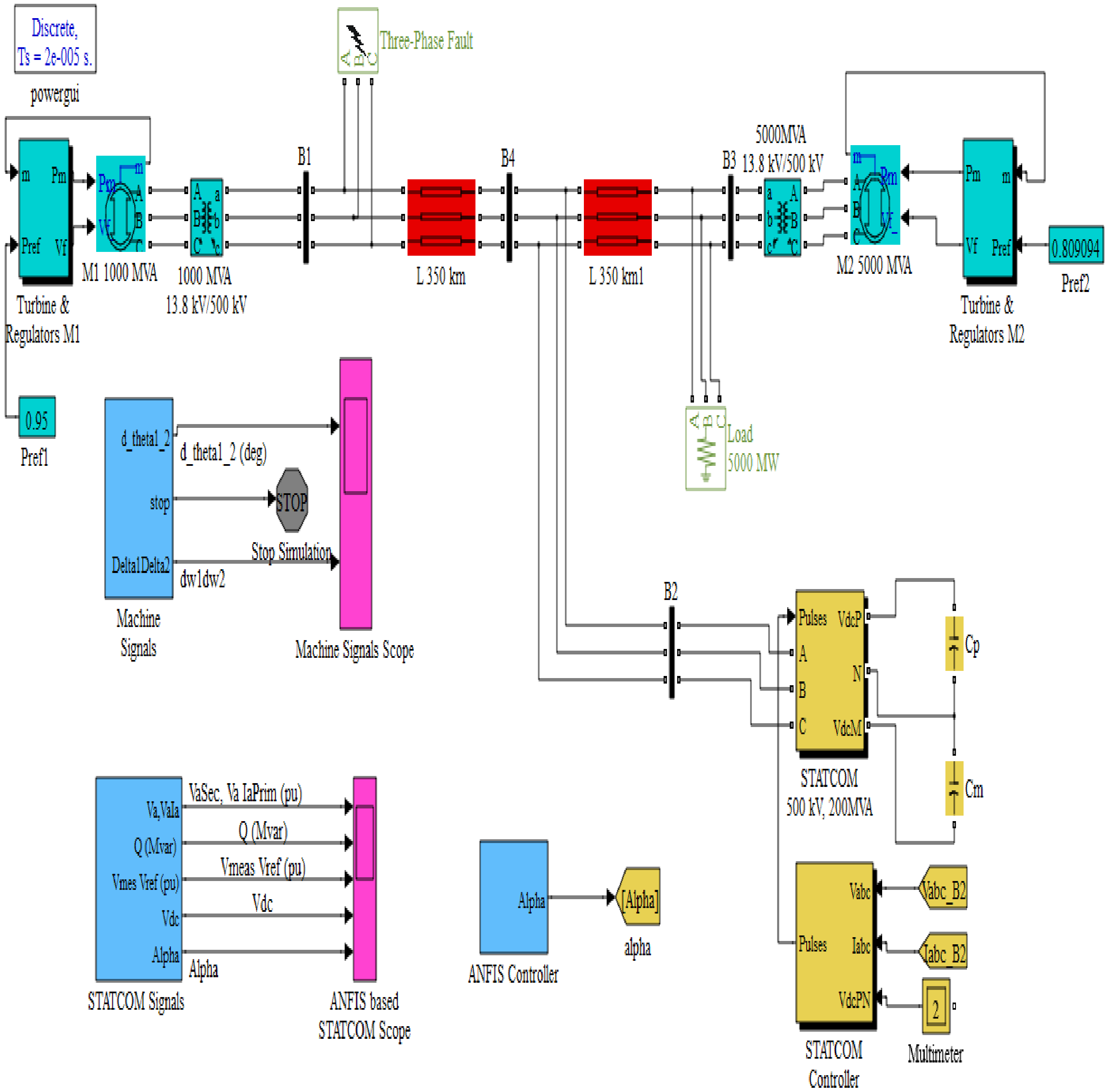

Figure 4.4 Two machine system installed with ANFIS based STATCOM controller

4.3. Simulation Results

4.3.1 System without STATCOM (under fault)

A three phase fault having clearing time of 0.1 sec is given during time period of 0.6 sec to 0.7 sec. System installed without STATCOM becomes unstable as shown by green line in Figure 4.5 and Figure 4.6 which tends towards infinity.

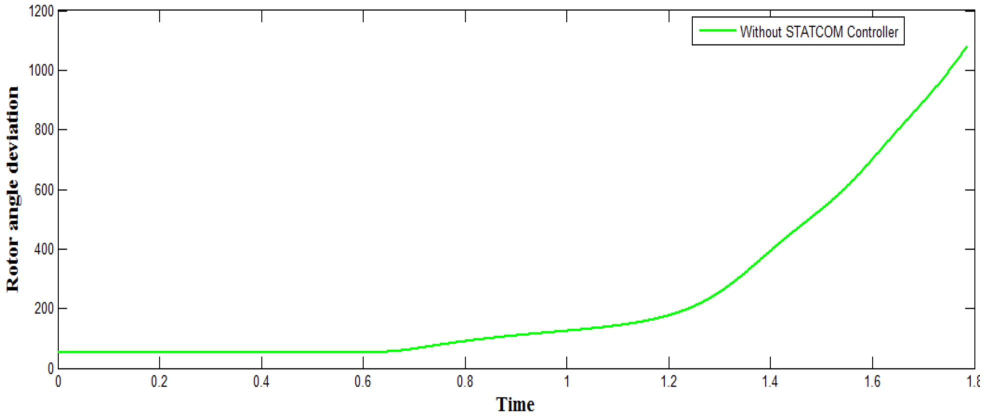

Figure 4.5 Deviation of Rotor angle with time

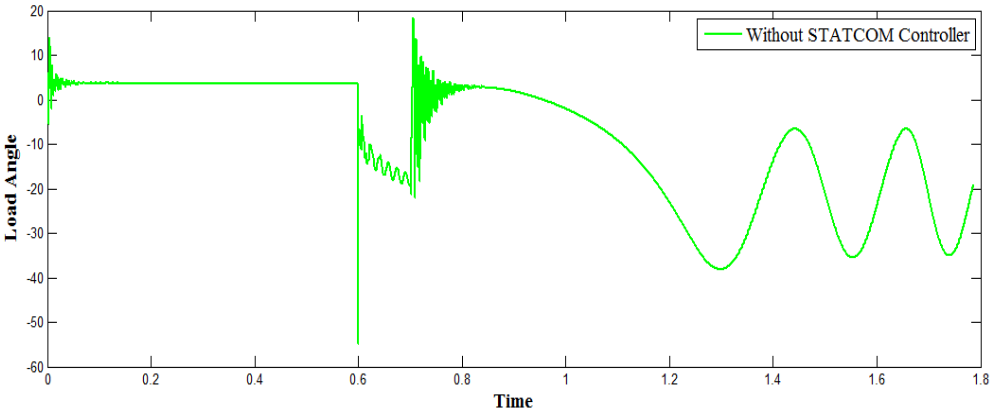

Figure 4.6 Load angle with time

4.3.2 System installed with PI based STATCOM (under fault):

Now System is installed with PI based STATCOM and fault having clearing time of 0.1 sec is given. System becomes stable after fault as shown in Figure 4.7 and Figure 4.8. Response of different parameters of STATCOM during fault is shown in Figure 4.9 to Figure 4.13

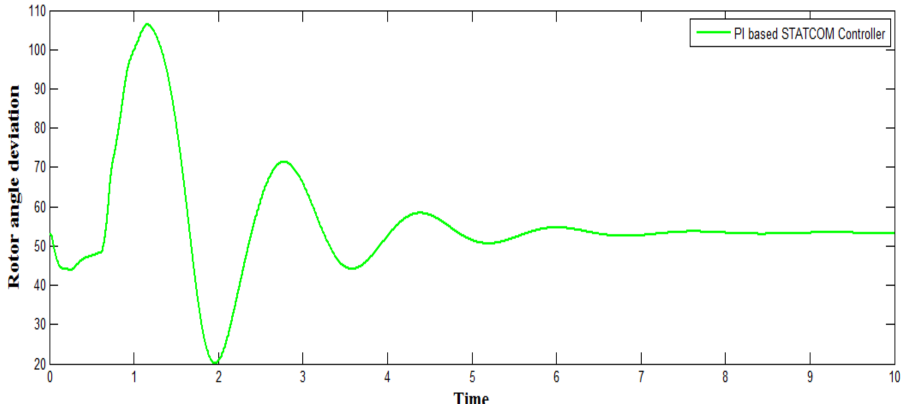

Figure 4.7 Rotor angle deviation with time

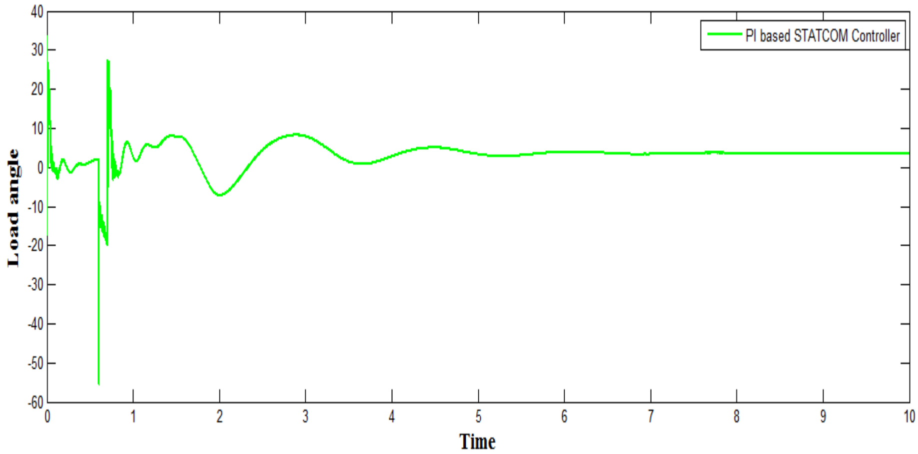

Figure 4.8 Load angle with time

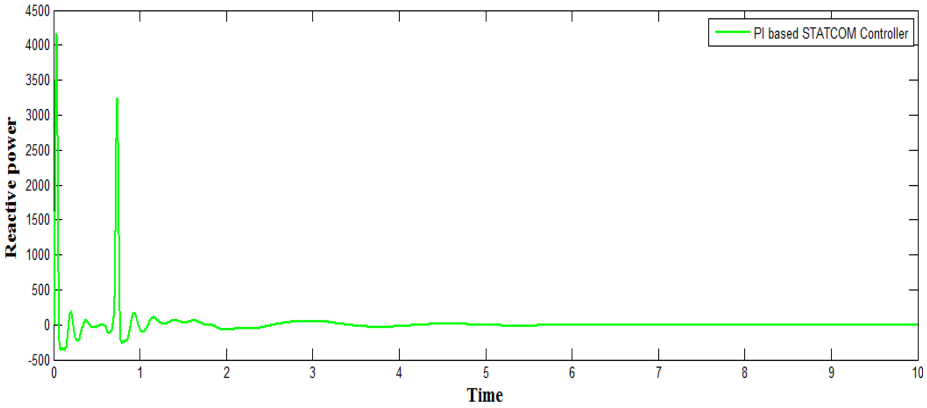

Figure 4.9 Reactive Power with time

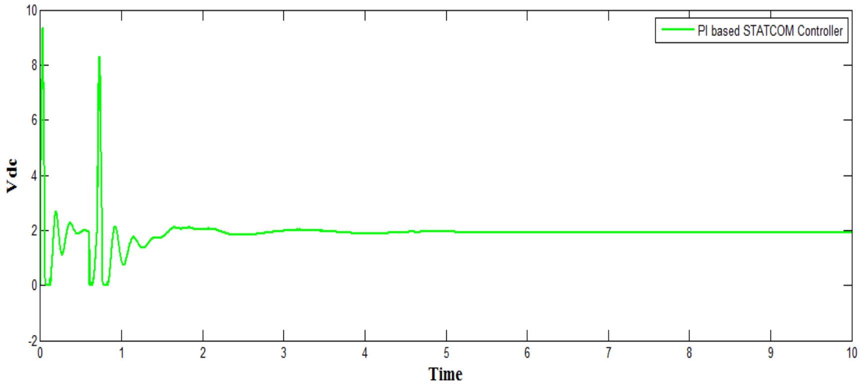

Figure 4.10 V_{dc} with time

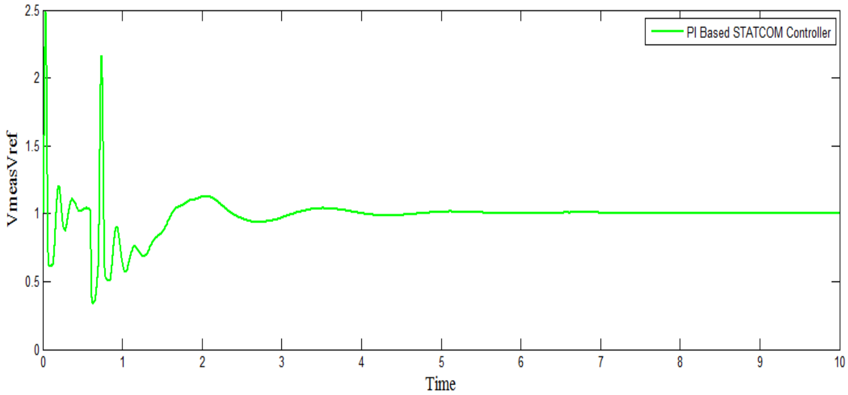

Figure 4.11 Vmeas vs Vref with time

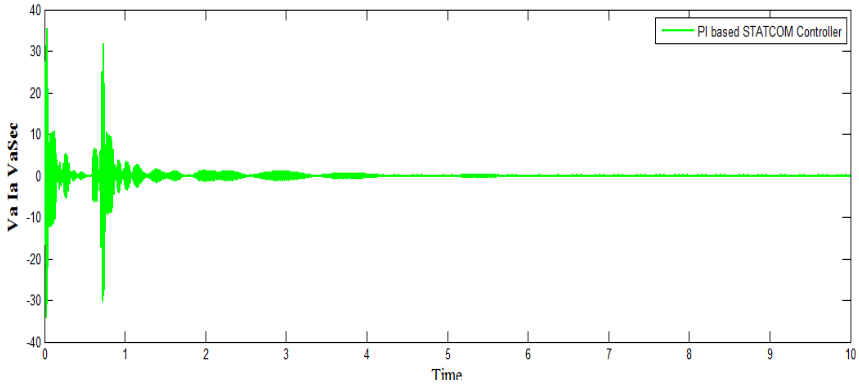

Figure 4.12 Vasec vs Va vs Ia with time

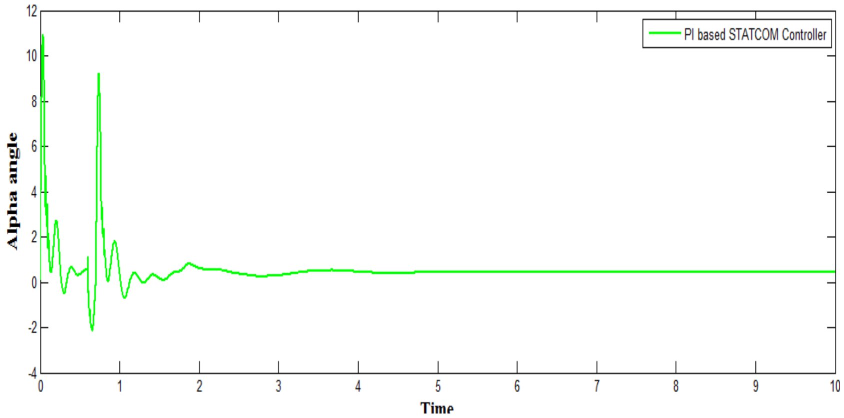

Figure 4.13 Alpha angle of VSC with time

4.3.3 System installed with Fuzzy based STATCOM controller (under fault):

Now System is installed with fuzzy based STATCOM Controller and fault having clearing time of 0.1 sec is given during time period of 0.6 sec to 0.7 sec. various responses under fault conditions are shown below:

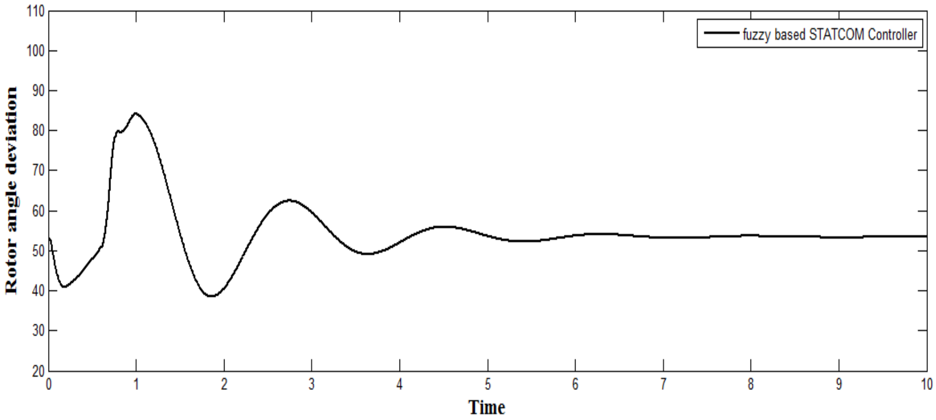

Figure 4.14 Rotor angle deviation with time

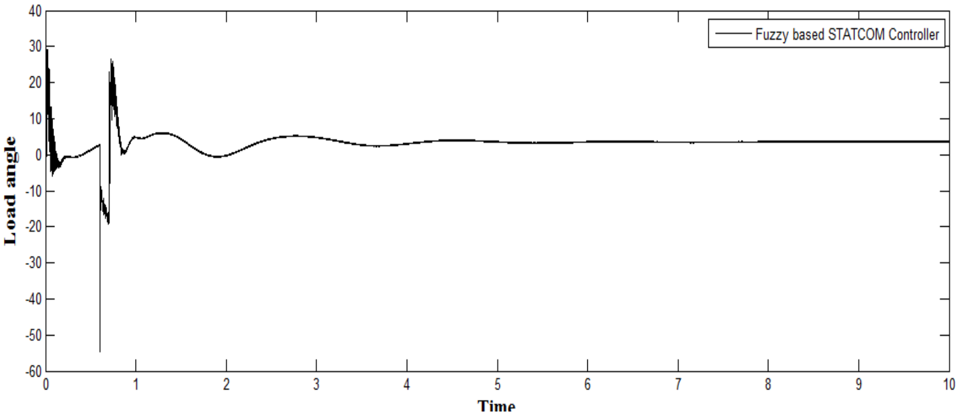

Figure 4.15 Load angle with time

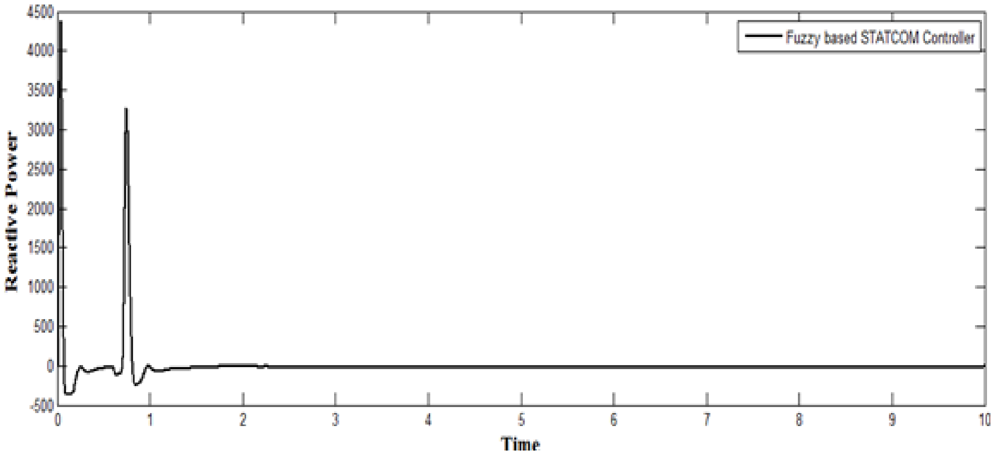

Figure 4.16 Reactive power with time

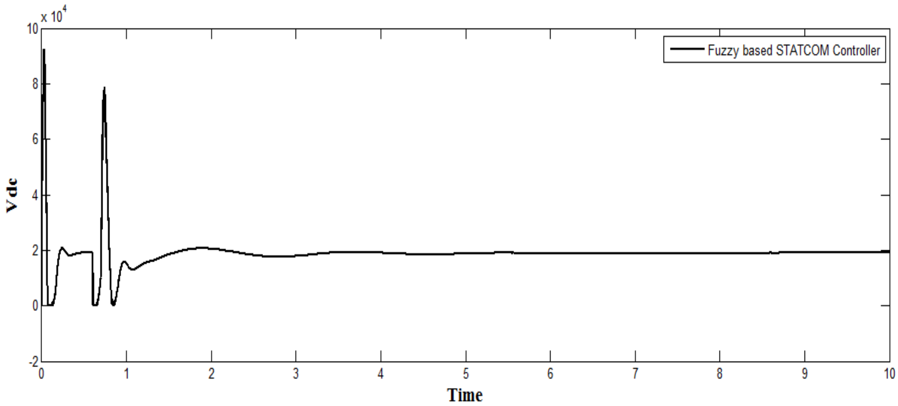

Figure 4.17 V_{dc} with time

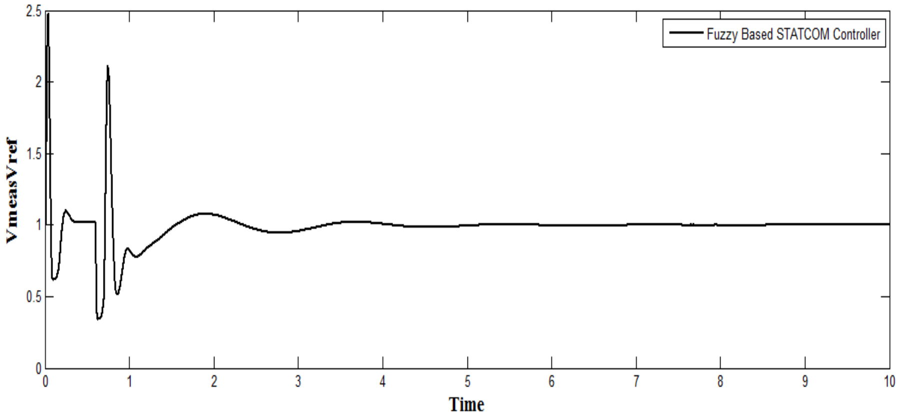

Figure 4.18 V_{meas} vs V_{ref} with time

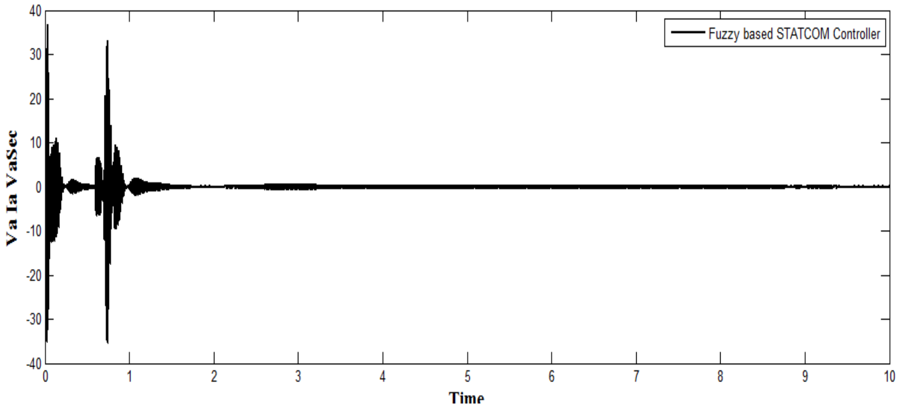

Figure 4.19 Va vs Ia vs Va_{Sec} with time

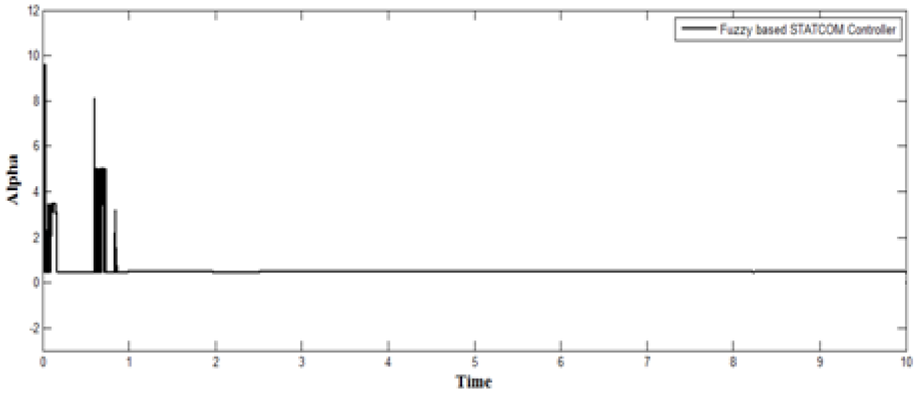

Figure 4.20 Alpha angle of VSC with time

4.3.4 System installed with Fuzzy-PI based STATCOM (under fault):

Now system is installed with Fuzzy-PI based STATCOM Controller and fault having clearing time of 0.1 sec is given. Various responses under fault conditions are shown below.

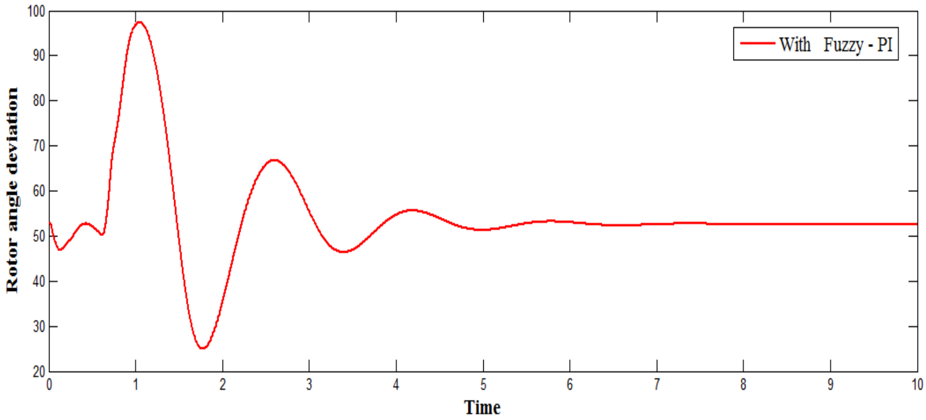

Figure. 4.21 Rotor angle deviation with time

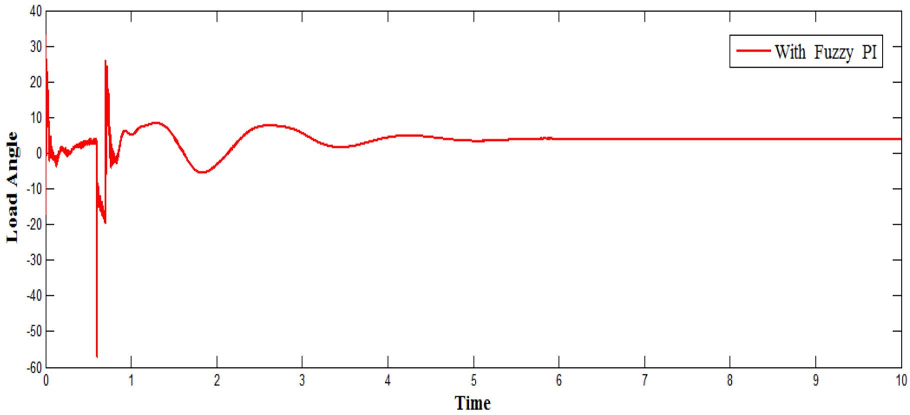

Figure 4.22 Load angle with time

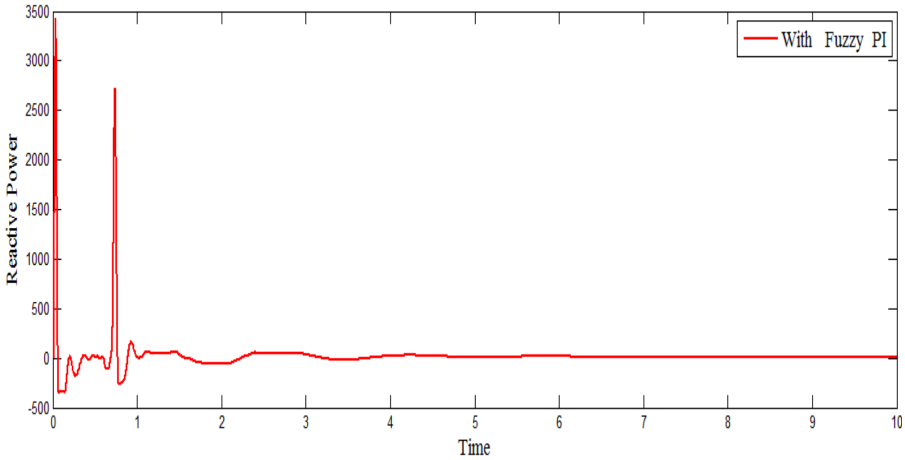

Figure 4.23 Reactive power with time

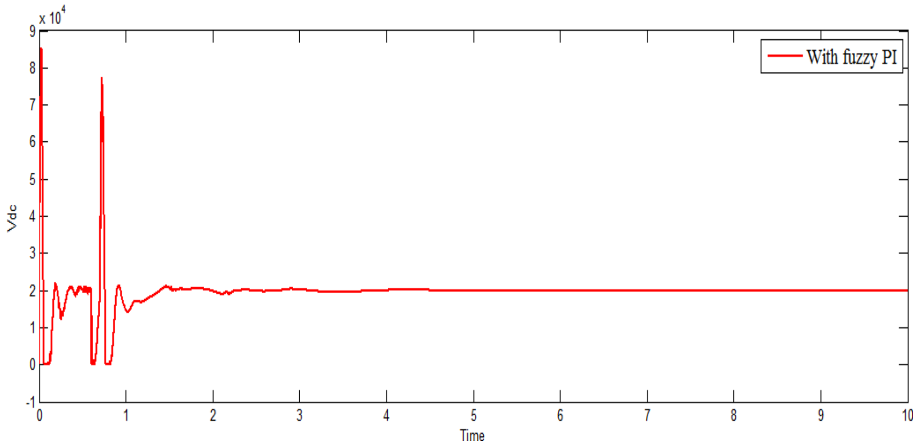

Figure 4.24 V_{dc} with time

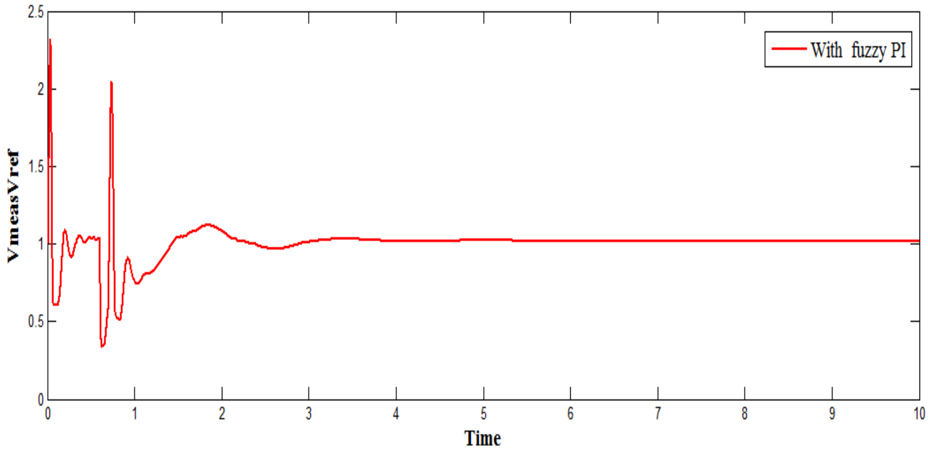

Figure 4.25 V_{meas} vs V_{ref} with time

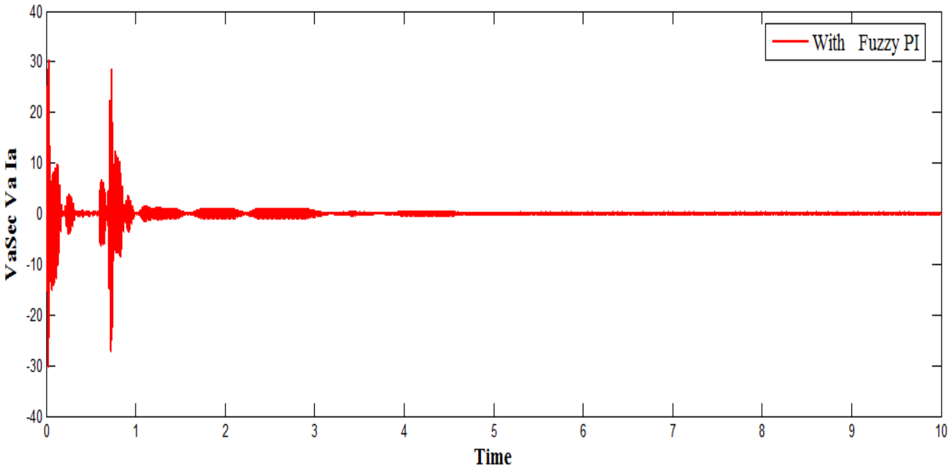

Figure 4.26 V_{aSec} vs V_a vs I_a

Figure 4.23 to Figure 4.26 shows the response of different parameters of Fuzzy-PI based STATCOM during fault.

4.3.5 System installed with ANFIS based STATCOM Controller (under fault):

A three phase fault having clearing time of 0.1 sec is given for time period of 0.6 to 0.7 sec. System installed without STATCOM becomes unstable after fault as shown by red line given in Figure 4.27, Figure 4.28, and Figure 4.29. Now System is installed with ANFIS based STATCOM Controller and fault having clearing time of 0.1 sec is given for same time period, system becomes stable after fault as shown by black lines in given Figure 4.27, Figure 4.28 and Figure 4.29.

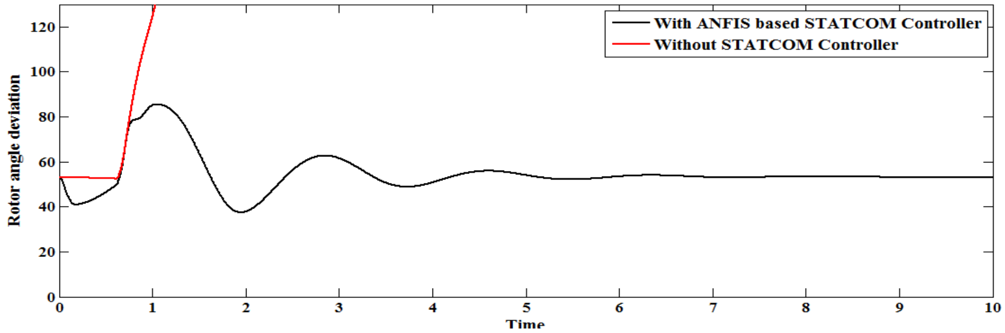

Figure 4.27 Rotor angle deviation with time

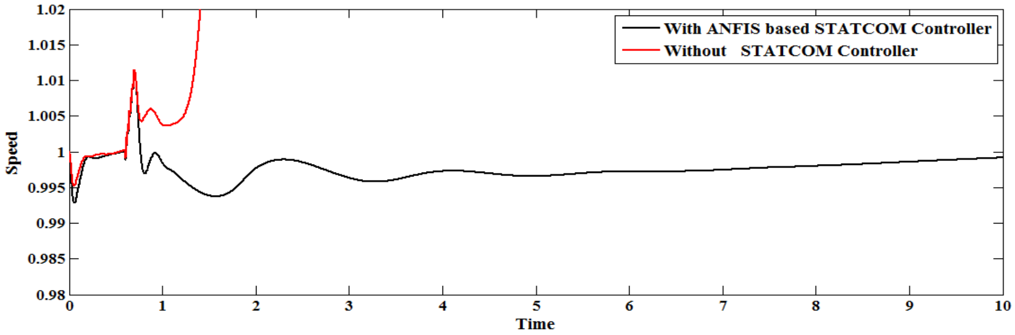

Figure 4.28 Speed with time

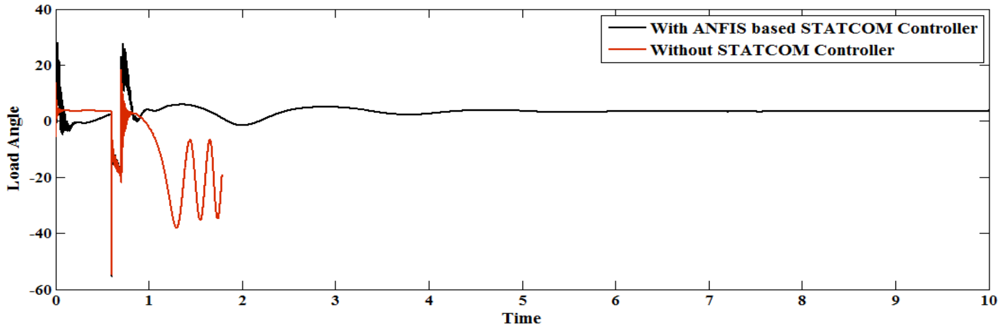

Figure 4.29 Load angle with time

Figure 4.27, Figure 4.28 & Figure 4.29 shows the comparison of difference of Rotor angle deviation, Speed of Generator and Load angle of a system installed without ANFIS based STATCOM Controller and a system installed with ANFIS based STATCOM Controller. By Analyizing this comparison it can be said that ANFIS based STATCOM is able to turn unstable system in to stable state and provide better stability. Figure 4.30, Figure 4.31, Figure 4.32 and Figure 4.33 shows the response of different parameters of STATCOM during fault.

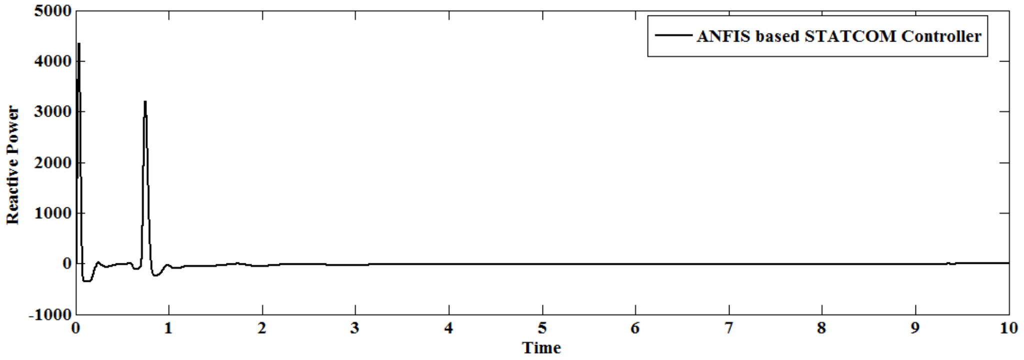

Figure 4.30 Reactive power with time

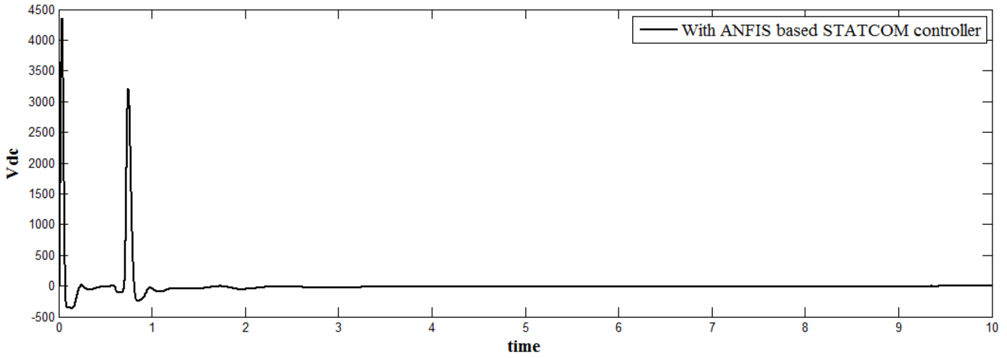

Figure 4.31 Vdc with time

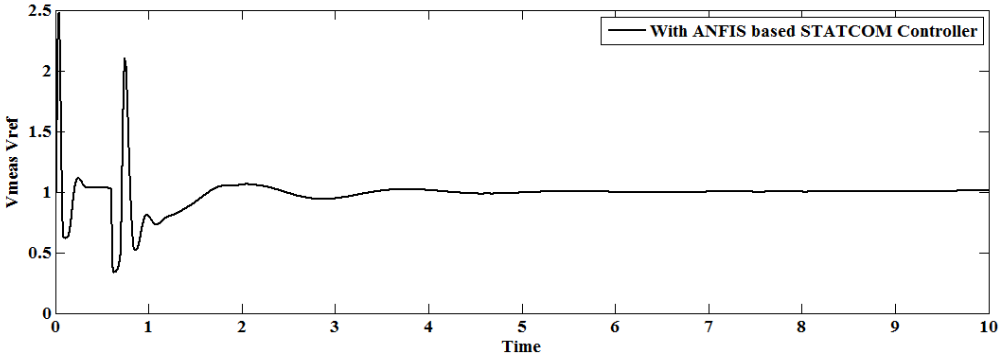

Figure 4.32 Vmeas vs Vref with time

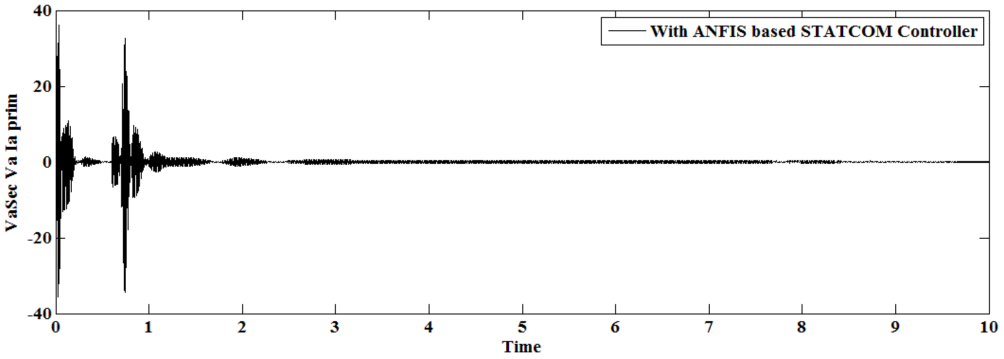

Figure 4.33 VaSec vs Va vs Ia with time

4.3.6 Comparison between PI based and Fuzzy based STATCOM controller:

Responses below shows the comparison between fuzzy based and PI based STATCOM controller

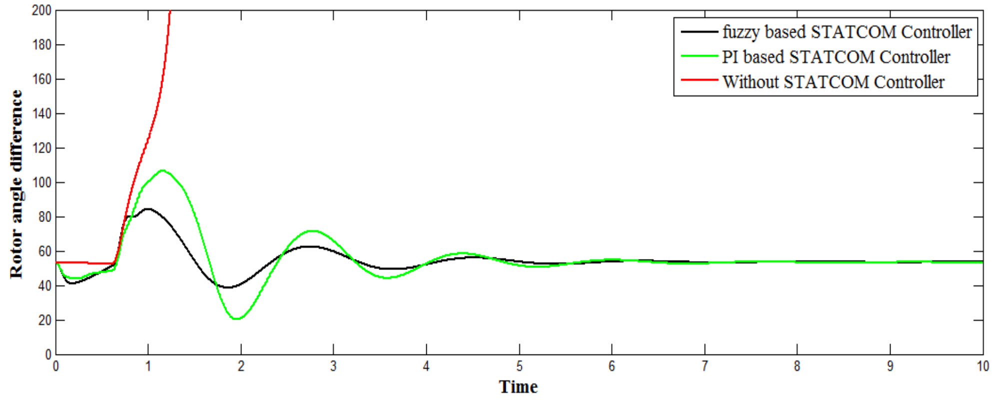

Figure 4.34 Rotor angle deviation with time

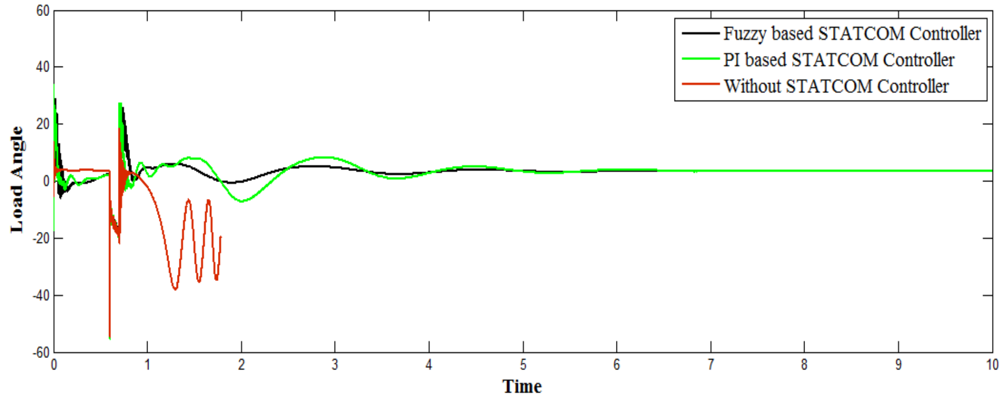

Figure. 4.35 Load angle with time .

From Figure 4.34 & Figure 4.35 it's clear that fuzzy based STATCOM controller is more successful in damping of rotor angle and Load angle variation as compared to PI based STATCOM

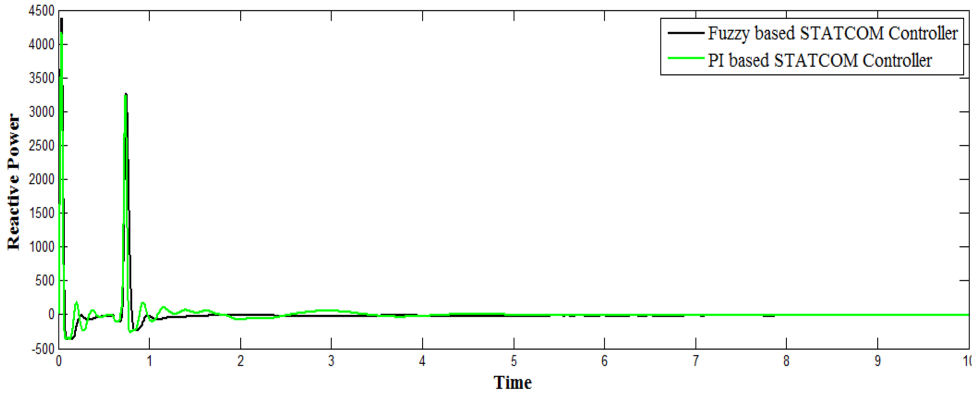

Figure 4.36 Reactive power with time

Figure.4.36 shows comparison between reactive power of fuzzy based and PI based STATCOM controller.

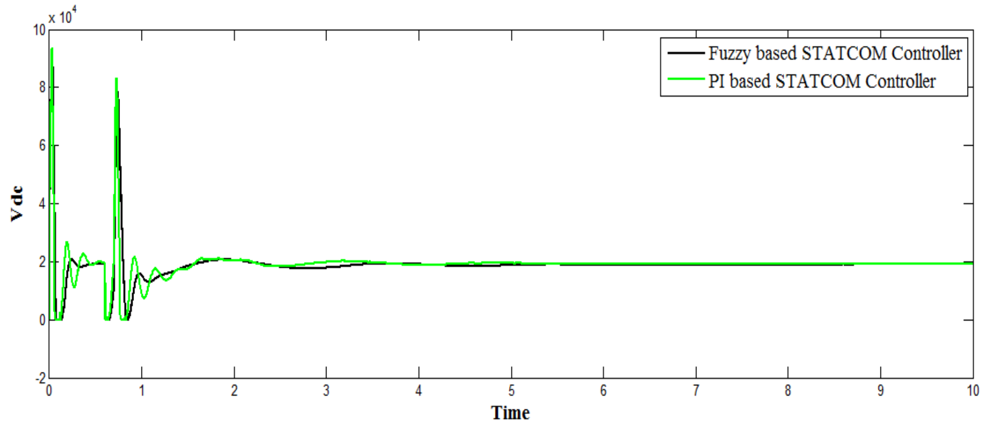

Figure 4.37 Vdc with time

Figure 4.37 shows the comparison between V_{dc} (voltage across Capacitor) of Fuzzy based STATCOM and conventional PI based STATCOM with time

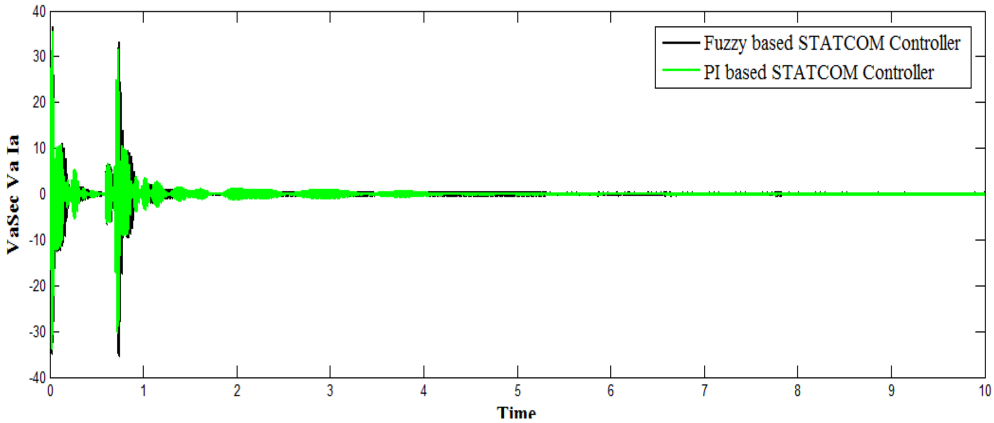

Figure 4.38 VaSec vs Va vs Ia with time

Figure 4.38 shows the comparison between voltage, current of bus B2 and transformer secondary voltage of Fuzzy based and PI based static synchronous compensator with time

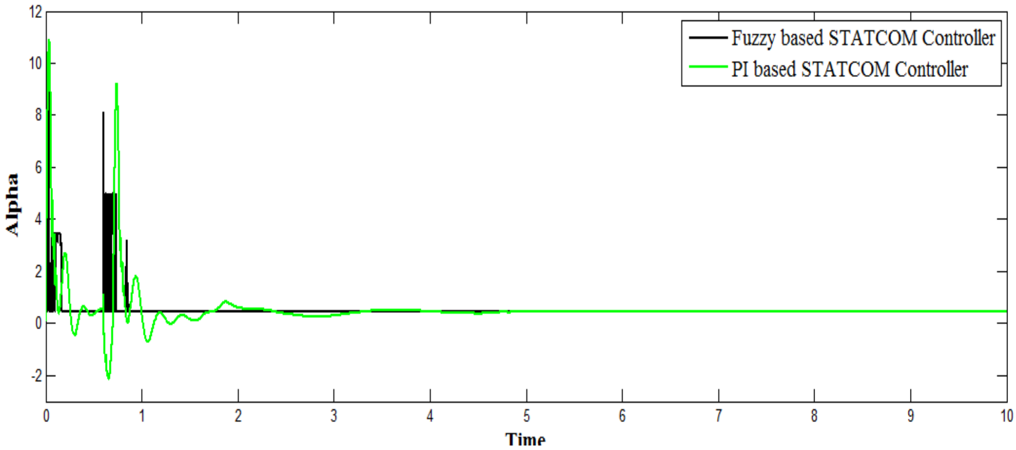

Figure 4.39 Alpha angle of VSC with time

Figure 4.39 shows the comparison between angle Alpha of voltage source converter of fuzzy based STATCOM controller and PI based STATCOM with time.

4.3.7 Comparison between PI and Fuzzy- PI based controller (under fault)

Case I.

A three phase fault having clearing time of 0.1 sec is given at 0.6 sec. Now System is installed with PI based or fuzzy-PI based STATCOM and fault having clearing time of 0.1 sec is given. Comparison between various responses of fuzzy-PI based and PI based STATCOM controller as shown in Figure 4.40 & Figure 4.41

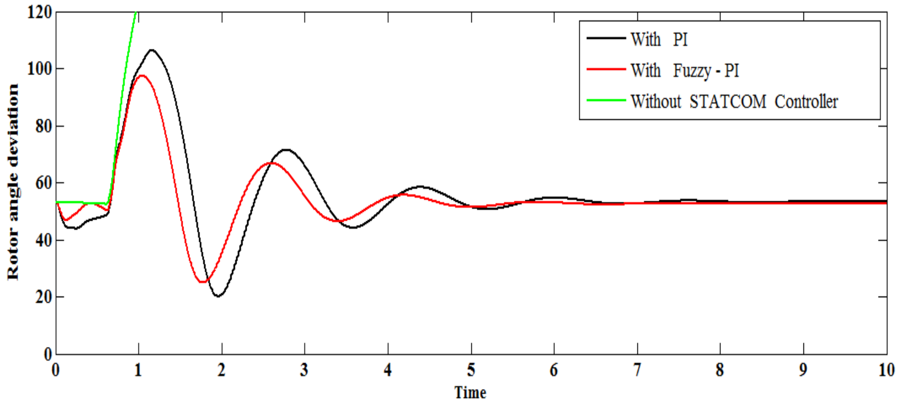

Figure 4.40 Rotor angle deviation with time

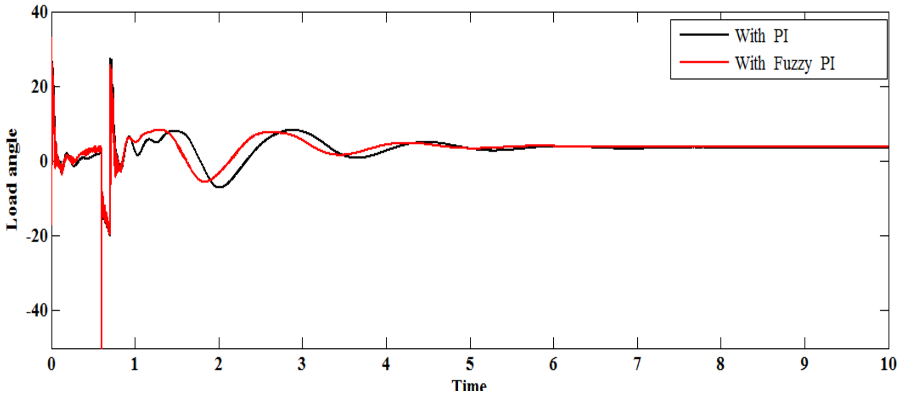

Figure 4.41 Load angle with time

From figure 4.40 & figure 4.41 it’s clear that fuzzy PI based STATCOM controller is more successful in damping of rotor angle and Load angle variation as compared to PI based STATCOM.

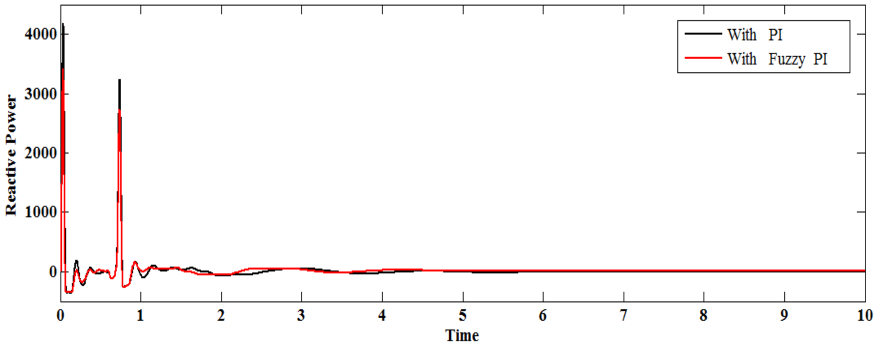

Figure 4.42 Reactive power with time

Figure 4.42 shows comparison between reactive power of fuzzy based and PI based STATCOM controller.

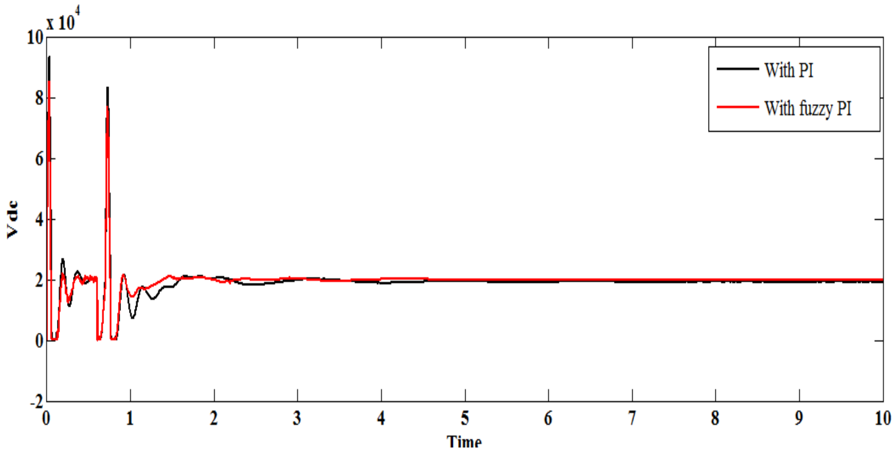

Figure 4.43 Vdc with time

Figure 4.43 shows the comparison between V_{dc} (voltage across Capacitor) of Fuzzy based STATCOM and conventional PI based STATCOM with time.

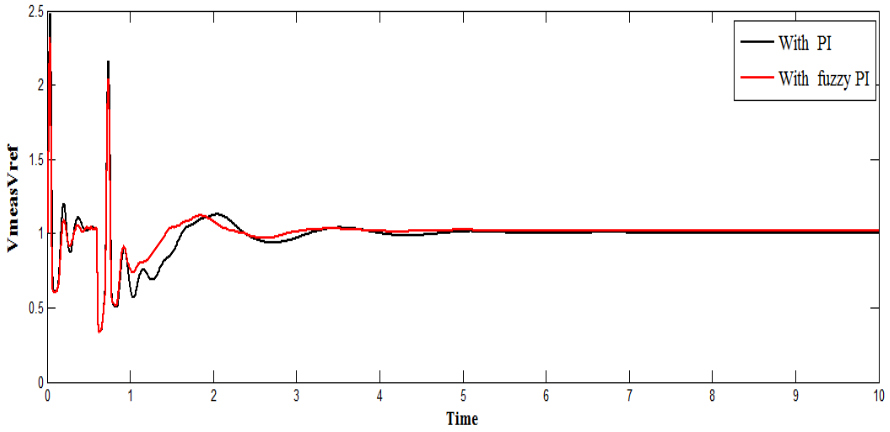

Figure 4.44 V_{meas} vs V_{ref} with time

Figure 4.44 shows the comparison between measured voltage (V_{meas}) and reference voltage (V_{ref}) of Fuzzy based STATCOM and PI based STATCOM with time.

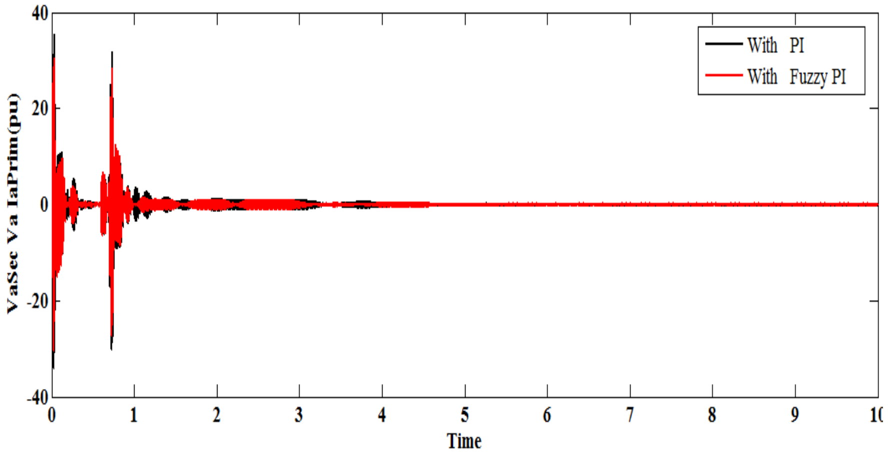

Figure 4.45 VaSec vs Va vs Ia with time

Figure 4.45 shows the comparison between voltage, current of bus B_2 and transformer secondary voltage of Fuzzy based and PI based static synchronous compensator with time.

CASE II

The design parameter of STATCOM i.e. the resistance (R_s) and leakage inductance (L_s) of the windings of single phase transformers used to implement the primary winding of the zigzag phase shifting transformer is changed. R_s is changed from 0.05 ohm to 0.08 ohm and Ls is changed from 0.05 H to 0.08 H. Effects of this changes is shown in Figure 4.46, Figure 4.47

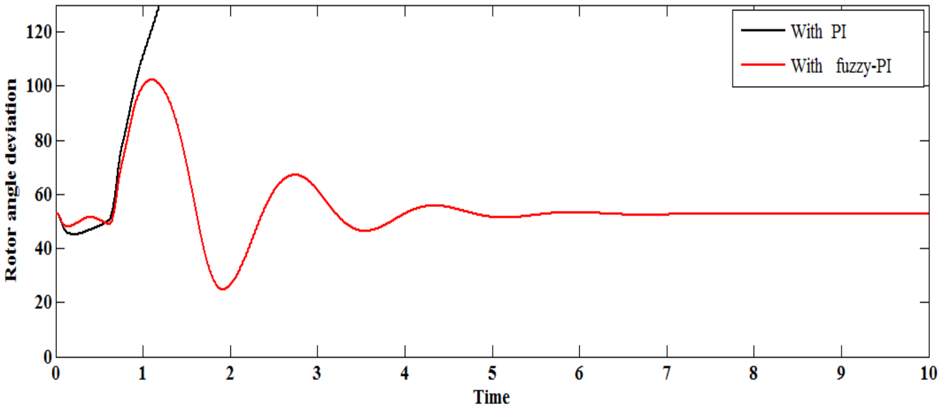

Figure 4.46 Rotor angle deviation with time

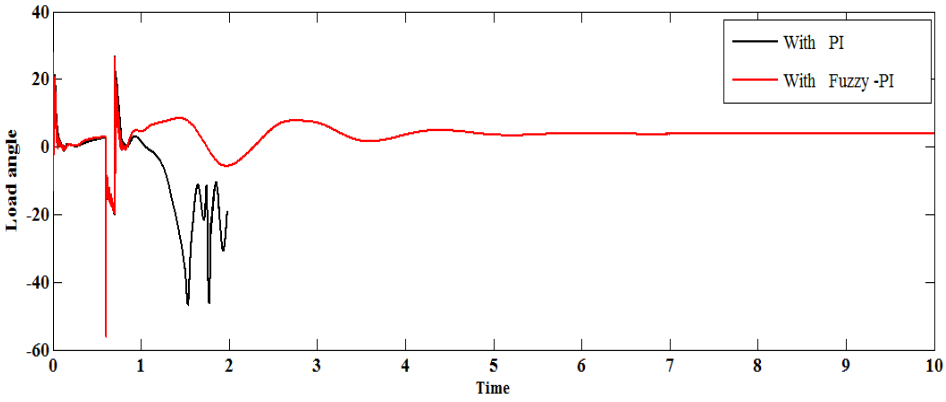

Figure 4.47 Load angle with time

CHAPTER 5

CONCLUSION & FUTURE SCOPE

5.1 Conclusion

In this Thesis, dynamic behaviour of two machine system installed with STATCOM is investigated under 3-phase fault. Fuzzy based STATCOM controller, ANFIS based STATCOM controller and Fuzzy-PI based STATCOM controller are design to improve the transient stability of the given system. Generator speed i.e. ω and its derivative i.e. $\frac{d\omega}{dt}$ are taken as input parameters while angle alpha i.e. α of voltage source converter is taken as output parameter for fuzzy based as well as ANFIS based STATCOM controllers. Controllers inputs are chosen carefully to provide better damping to the system and its range are determined by the simulation results of fuzzification process. For Fuzzy-PI based STATCOM controller, error i.e. difference of V_{meas} and V_{ref} and its derivative are taken as input parameters for voltage regulator similarly for current regulator difference of I_q and I_{q_ref} and its derivative are taken as input while K_p and K_i are taken as output parameters. Proposed controllers are implemented using MATLAB/SIMULINK. Fuzzy based STATCOM controller and Fuzzy-PI based STATCOM controller compared with conventional PI based STATCOM controller. Simulation results indicate that the Fuzzy based STATCOM controller and Fuzzy-PI based STATCOM controller installed with two machine system provides better damping characteristics as compared to conventional PI based STATCOM controller and provides improved transient stability as compared to conventional Fuzzy-PI based STATCOM controller.

5.2 Future Scope

In the following, some recommendations are given for future research in this area :

1) To design Fuzzy-PI STATCOM controller for improving transient stability in multimachine system.
2) To design ANFIS based controller for STATCOM coupled with energy storage system and compare performance with conventional PI based controller for transient improvement of power system

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