Sudan University of Science and Technology

College of Graduate Studies

Design and Simulation of Fuzzy Logic Controller for DSTATCOM in Power System

تصميم و محاكاة متحكم منطقي غامض لمعوض التوزيع المتزامن في منظومة القوى الكهربية

A Dissertation Submitted in Partial Fulfillment for the Requirement of M.Sc. Degree in Electrical Engineering (Control and Microprocessor)

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الأيـــــــــــــــة

(لا يُكَلِّفُ اللَّهُ نَفْساً إِلَّا وُسْعَهَا لَهَا مَا كَسَبَتْ وَعَلَيْهَا مَا اكْتَسَبَتْ رَبَّنَا لا تُؤَاخِذْنَا إِنْ نَسِينَا أَوْ أَخْطَأْنَا رَبَّنَا وَلا تَحْمِلْ عَلَيْنَا إِصْراً كَمَا حَمَلْتَهُ عَلَى الَّذِينَ مِنْ قَبْلِنَا رَبَّنَا وَلا تُحَمِّلْنَا مَا لا طَاقَةَ لَنَا بِهِ وَاعْفُ عَنَّا وَاغْفِرْ لَنَا وَارْحَمْنَا أَنْتَ مَوْلانَا فَانْصُرْنَا عَلَى الْقَوْمِ الْكَافِرِينَ)

(البقرة:286)

DEDICATIONS

To my father’s soul,,,,,,,

To my beloved mother,,,,,,

To my brothers and sisters,,,,,

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I would like to thank many people who helped and supported me during the whole work of my thesis.

Words are not enough to thank my guide. I take this opportunity to acknowledge the guidance and encouragement of my supervisor **Dr.AWADALLA TAYFOUR**. I have been inspired by his enthusiasm optimism his attention to detail and energetic application to any problem. I value his concern and support at all time, good and bad.

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Above all I thank the almighty god ALLAH who is being with me and showers his blessings and grace towards me in all walks of my life.

ABSTRACT

The electrical energy is one of the easily used forms of energy. It can easily converted to other forms of energy. With the advancement of technology, the dependency on the electrical energy has been increased greatly in different applications which have a large importance in life. At the same time these applications demand qualitative energy.

This study mainly presents the Distribution Static Compensator (DSTATCOM) and control methodology of Direct Current (DC) capacitor voltage. Generally, the DC capacitor voltage is regulated using a Proportional Integral (PI) controller when various control algorithms are used for load compensation. However, during load changes, there is considerable variation in dc capacitor voltage which might affect compensation. In this study, a fuzzy logic based supervisory method is proposed to improve transient performance of the dc link. The fuzzy logic based supervisor varies the proportional and integral gains of the PI controller during the transient period immediately after a load change.

A considerable reduction in the error in DC link capacitor voltage during load changes compared to a normal PI controller is obtained. The performance of the proposed strategy is proved using detailed simulation studies.

مستخلص

تعد الطاقة الكهربية واحدة من أهم أشكال الطاقة حيث يسهل تحويلها من شكل إلى آخر. و بالتقدم التكنولوجي نجد أنه قد إزدادت الإعتمادية عليها بصورة واسعة في مختلف التطبيقات ذات الأهمية الكبيرة في الحياة و في الوقت نفسه فإن هذه التطبيقات تتطلب الجودة في هذه الطاقة. يقدم هذا البحث معوض التوزيع الثابت المتزامن و آلية التحكم في جهد مكثف التيار المستمر. عادة جهد المكثف يتم تنظيمه عن طريق حاكمة تناسبية تكاملية للقيام بتعويض الأحمال. عند حدوث تغيرات في هذه الأحمال يجب أن تكون هناك بالمقابل تغيرات في جهد المكثف و الذي بدوره يؤثر في عملية التعويض.

في هذا البحث تم إقتراح طريقة مراقبة إعتماداً على المنطق الغامض للقيام بتحسين أداء رابط التيار المستمر في الحالة العابرة. هذا المراقب الغامض يقوم بتغيير الكسب التناسبي و التكاملي للحاكمة التناسبية التكاملية في الفترة العابرة مباشرة بعد تغير الحمل. و قد تم الحصول على انخفاض ملحوظ في قية خطأ جهد مكثف الرابط في حالة تغير الحمل مقارنة باستخدام الحاكمة التناسبية التكاملي المعتادة.نم إثبات أداء هذا النظام المقترح بإستخدام دراسات محاكاة مفصلة.

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LIST of ABBREVIATIONS

ANFIS	Adaptive Neuro Fuzzy Inference System
AC	Alternative Current
DSTATCOM	Distribution Static Compensator
DVR	Dynamic Voltage Restorer
FACTS	Flexible AC Transmission System
FIS	Fuzzy Inference System
FLC	Fuzzy Logic Controller
GTO	Gate Turn-off
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated Gate Bipolar Transistors
IGCT	Integrated Gate Commutated Thyristors
IPFC	Interline Power Flow Controller
NL	Negative Large
NM	Negative Medium
NS	Negative Small
PCC	Point of Common Coupling
PS	Positive Small
PM	Positive Medium
PL	Positive Large
PI	Proportional Integral
PID	Proportional Integral Derivative
PQ	Power Quality

PWM	Pulse Width Modulation
SRF	Synchronously Rotating d-q Frame
SVC	Static Var Compensator
UPFC	Unified Power Flow Controller
VSC	Voltage Source Converter
VSI	Voltage Source Inverter

CHAPTER ONE
INTRODUCTION

1.1 General

The Flexible AC Transmission Systems (FACTS) technology is a new research area in power engineering. It introduces the modern power electronic technology into traditional AC power systems and significantly enhances power system controllability and transfer limit. FACTS devices provide a better adaptation to varying operational conditions and improve the usage of existing installations. They have basic applications such as power flow control, increasing of transmission capability, voltage control, reactive power compensation, stability improvement and power quality improvement.The DSTATCOMP is technology of the FACTS and it is based on a voltage-source inverter [1].

Fuzzy logic is used to represent qualitative knowledge, and provides interpretability to system models. Zadeh has summarized fuzzy logic as a body of concepts and techniques for dealing with imprecision, information granulation, approximate reasoning and computing with words rather than numbers. Over the past two decades, there has been a tremendous growth in the use of fuzzy logic controllers in power systems as well as power electronic applications [2].

1.2 Problem Statement

The capacitor banks were used for reactive power compensation and voltage regulation, but they have great problems such as stress and sudden changes in capacitors. Also their response to transient errors is very slow, so they were replaced by Static Var Compensators which will reduce the time of response and improve the voltage stability .But the SVC transient stability is low, so DSTATCOM is proposed to be used instead of these devices because it has fast response in compensation and voltage profile correction.

1.3 Objectives

The main aims of this study are to:

- Develop the mathematical and computer model of the DSATCOM.
- Design fuzzy logic controller for DSTATCOM.
- Carry out the simulation results of the proposed control system.

1.4 Methodology

- Study of related literature reviews to understand the operation of DSTATCOMP.
- Build the mathematical and computer model of DSTATCOM using MATLAB program.
- Use of Mamdani fuzzy logic type to design the fuzzy controller for the system.
- Use of MATLAB TOOLBOX to model the fuzzy logic based system.
- Simulate the proposed control system using MATLAB SIMULINK.

1.5 Layout

This dissertation consists of five chapters including chapter one. Each chapter is organized in the following way:

Chapter Two deals with the power quality problems and their effect on the consumer appliances. It also deals with flexible AC transmission system controllers; their classifications and applications in distribution system. It focuses on DSTATCOM operating principle, its voltage regulation, DC bus voltage regulation and the applications of DSTATCOM .It also focuses on fuzzy logic, fuzzy sets, member ship functions, fuzzy control system elements and fuzzy logic implication techniques. Chapter Three deals with the modeling of DSTATCOM. It also presents the design of fuzzy logic based supervision of Dc link PI control for that device. Chapter Four presents the MATLAB simulation results of the proposed fuzzy PI controller. This chapter discusses how the selected controller works practically. Chapter Five presents the conclusion of the work done along with the recommendations.

CHAPTER TWO
LITERATURE REVIEW

2.1 Power Quality

Power quality issues, causes, effects and analysis have become an important aspect of research work in recent days. As the power is generated in power stations which are generally far away from load centers, the huge amount of power generated from a generating station is transported to the consumer through transmission lines. The transmission of power from the generating point to the point of consumption is combined with variations of weather, variations in loads, variations in demands etc. which compromises the quality of power. Industrial and commercial consumers of electrical power are becoming increasingly sensitive to power quality problems [3]. Reliability and quality are two important parameters in the field of power engineering. Combining today's utility power with the ever increasing quantity of electrical sensitive load yields one of the major contributors to downtime in business and industries today. Issues of deregulation, standards and customer awareness (economics and legal) have brought forth a great deal of focus and motivation in these areas. Tremendous dedication from engineers as well as huge amounts of revenue has been spent to enhance the quality and reliability of electricity delivery. Power quality problem is described as the deviation in voltage, current and frequency from its nominal value in a power system [4]. Various power quality problems such as voltage sag, swell, fluctuation, harmonic distortion, unbalance and transient may have impact on customer devices which will cause malfunctions and loss of production [3].

2.1.1 Causes of power quality problem

Some common disturbances which may cause power quality problems are listed below:

- Lightning and natural phenomena.
- Formation of snow on transmission line, storm etc.
- Energization of capacitor banks and transformers.

- Switching or start-up of large loads e.g. induction motors.
- Operation of non-linear and unbalanced loads.
- Failure of equipment, e.g. transformers and cables.
- Wrong manoeuvres in distribution substations and plants.

The main cause of power quality problem is the short circuit fault occurring in the distribution side. This short circuit can cause a huge increase in the system current and consequently a large voltage drop in the impedance of the supply system [5].

2.1.2 Effects of power quality problem

Poor electric power quality has many harmful effects on power system devices and consumer goods. These effects are so dangerous that it is not visible until failure occurs in the equipments. Even if there is no occurrence of failure of the equipment, there will be losses and heating in the equipment which will ultimately reduce the life span of the equipment. When harmonics are added to the supply voltage equipment could receive high value of instantaneous voltage and may be susceptible to failure. This high voltage may also force electronic components of power system to operate in the saturation, producing additional harmonics and disturbances. The effects of poor power quality on capacitors, rotating machines, cables and transformers, fuses, and customers' equipment creates heating, noise, poor performance etc. Premature failure of distribution transformer due to heating can be caused by harmonics. Due to power quality problem there is huge power loss in the transformer, motors and transmission lines, specifically due to harmonics (e.g., inter and subharmonics) [6]. Due to sudden rise in voltage and/or current, failure of power system components and customer loads can occur.

2.2 Flexible AC Transmission System Controllers

Flexible AC Transmission System (FACTS) is defined as alternating current transmission systems incorporating power electronic-based and other static controllers to enhance controllability and increase power transfer capability. The FACTS controller is defined as a power electronic based system and other static equipment that provide control of one or more AC transmission system parameters.

Depending on the power electronic devices used in the control, the FACTS controllers can be classified as variable impedance type and Voltage Source Converter (VSC) based type. The variable impedance type controllers include Static Var Compensator (SVC), Thyristor Controlled Series Capacitor or compensator (TCSC) and Thyristor Controlled Phase Shifting Transformer (TCPST). The VSC based FACTS controllers are Static synchronous Compensator (STATCOM),Static Synchronous Series Compensator (SSSC),Interline Power Flow Controller (IPFC) and Unified Power Flow Controller (UPFC).

The FACTS controllers based on VSC have several advantages over the variable impedance type. For example, a STATCOM is much more compact than a SVC for similar rating and is technically superior. It can supply required reactive current even at low values of the bus voltage and can be designed to have in built short term overload capability. Also, a STATCOM can supply active power if it has an energy source or large energy storage at its DC terminals [7].

2.3 Distribution Static Compensator

DSTATCOM is a shunt connected device designed to regulate the voltage either by generating or absorbing the reactive power. The schematic diagram of a D-STATCOM is as shown in Figure 2.1 which contains DC capacitor, Voltage Source Inverter (VSI), coupling transformer and reactor.

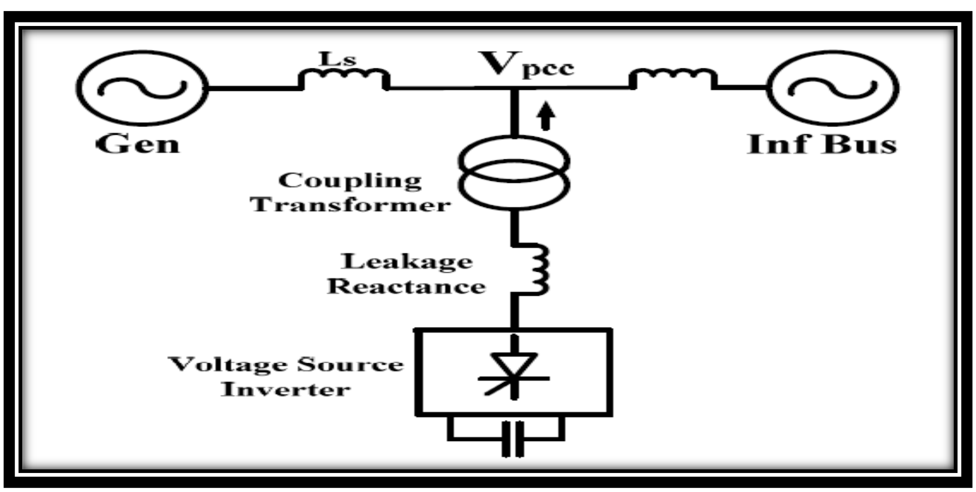

Figure.2.1: Schematic diagram of D-STATCOM

As in the case of Dynamic Voltage Regulator (DVR), the VSI generates voltage by taking the input from the charged capacitor. It uses Pulse Width Modulation (PWM) switching technique for this purpose. This voltage is delivered to the system through the reactance of the coupling transformer. The voltage difference across the reactor is used to produce the active and reactive power exchange between the STATCOM and the transmission network [8]. This exchange is done much more rapidly than a synchronous condenser and improves the performance of the system.

2.3.1 Operating principle

A D-STATCOM is capable of compensating either bus voltage or line current. It can operate in two modes based on the parameter which it regulates [9]. The operation modes of DSTATCOM are:

• **Voltage mode operation**

In this mode, it can make the bus voltage to which it is connected a sinusoid. This can be achieved irrespective of the unbalance or distortion in the supply voltage.

• **Current mode operation**

In this mode of operation, the D-STATCOM forces the source current to be a balanced sinusoid irrespective of the load current harmonics.

The basic operating principle of a D-STATCOM in voltage sag mitigation is to regulate the bus voltage by generating or absorbing the reactive power. Therefore, the DSTATCOM operates either as an inductor or as a capacitor based on the magnitude of the bus voltage.

• **Inductive mode operation**

If the bus voltage magnitude is more than the rated voltage then the D-STATCOM acts as an inductor absorbing the reactive power from the system. The circuit and phasor diagram are shown in Figure 2.2.

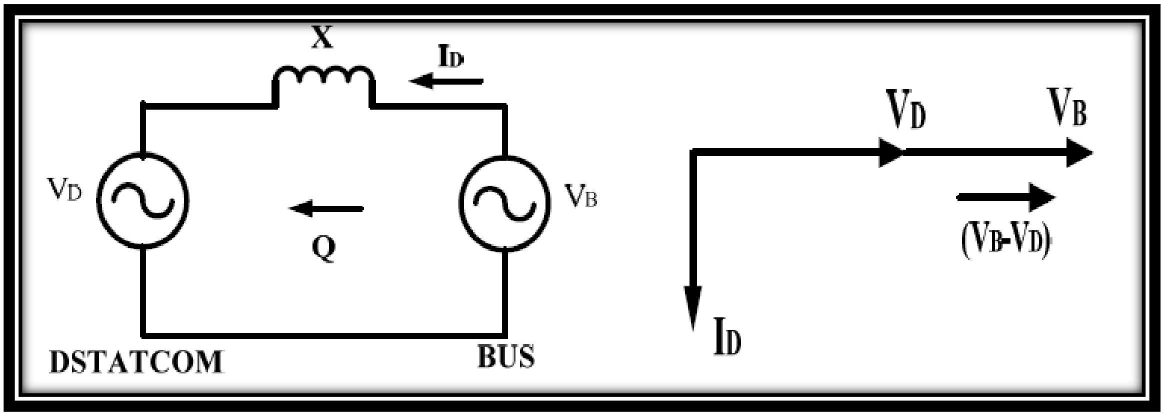

Figure 2.2: Inductive mode of operation

• **Capacitive mode operation**

If the bus voltage magnitude (VB) is less than the rated voltage then the D-STATCOM acts as a capacitor generating the reactive power to the system. The circuit and phasor diagram of this mode of operation are shown in Figure 2.3.

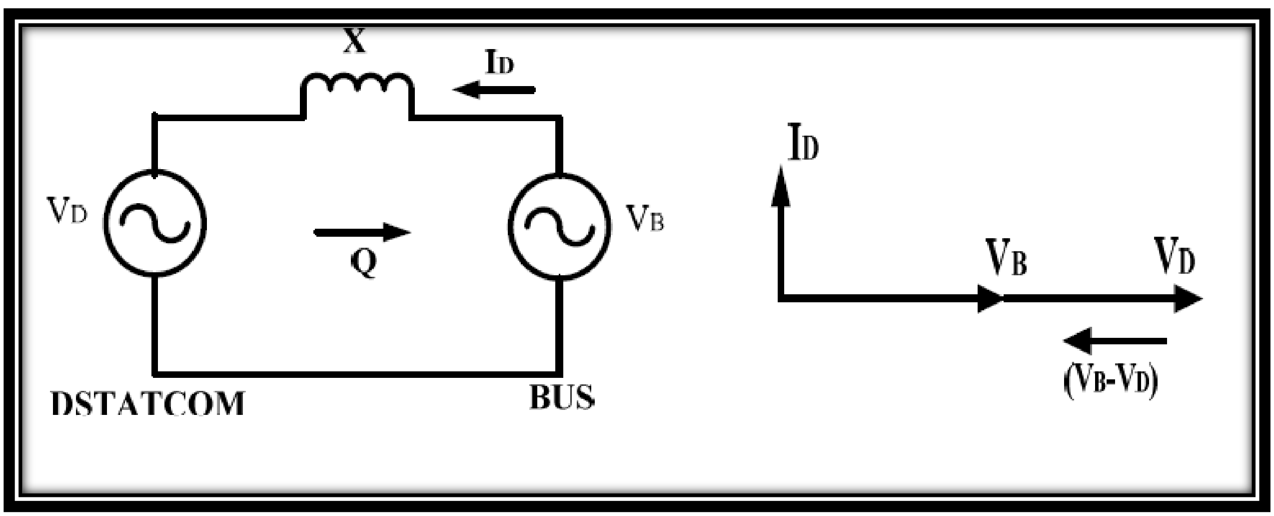

Figure 2.3: Capacitive mode of operation

2.3.2 Control strategy

The main aim of the control strategy implemented to control a D-STATCOM used for voltage mitigation is to control the amount of reactive power exchanged between the STATCOM and the supply bus. When the Point of Common Coupling (PCC) voltage is less than the reference (rated) value then the D-SATACOM generates reactive power and when PCC voltage is more than the reference (rated) value then the D-SATACOM absorbs reactive power[.

To achieve the desired characteristics, the firing pulses to PWM VSI are controlled.

The actual bus voltage is compared with the reference value and the error is passed through a Proportional Integral (PI) controller. The controller generates a signal which is given as an input to the PWM generator. The generator finally generates triggering pulses such that the voltage imbalance is corrected. The block diagram of the control circuit is shown in Figure 2.4.

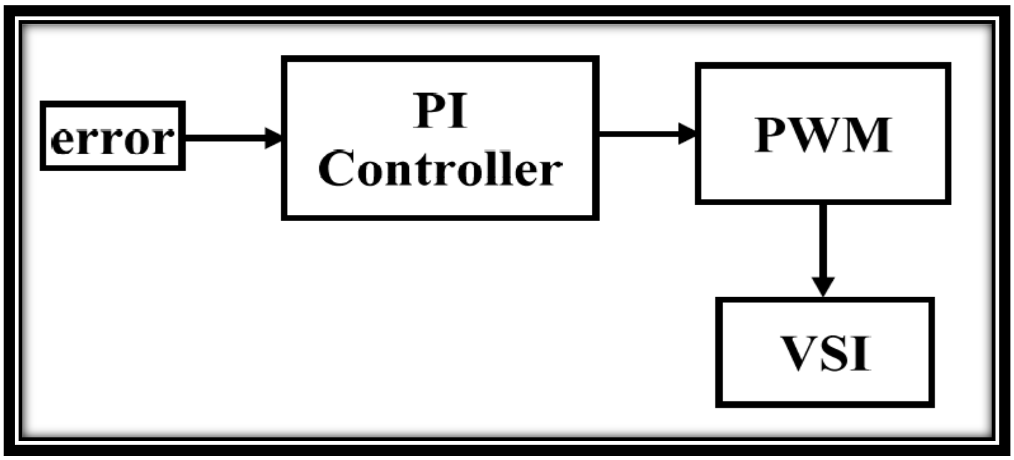

Figure 2.4: Block diagram of the control circuit of D-STATCOM

2.3.3 DSTATCOM voltage regulation

In line voltage regulation part is performed by a feedback control. Two coordinates V_d and V_q is compared with harmonic extracted voltage $V_{hd}^{*}$and V_{hq}^{*}. A gain Kv amplifies and to produce current references for harmonic damping I_{cd}, I_{cq} and I_o as given in (2.1), (2.2) and (2.3). The current reference for the voltage source inverter is the sum of the current references from the three parts, as follows:

$$Icd^{*}(s) = Kv(Gh\, Vhd^{*} - Vd) + (Vdc^{*} - Vdc) \quad (2.1)$$

$$Icq^{*}(s) = (Gh\, Vhq^{*} - Vq) \quad (2.2)$$

$$Io^{*}(s) = \frac{1}{3(Va+Vb+Vc)} \quad (2.3)$$

The obtained current reference is converted three phase current reference by inverse D– Q transformation. The three phase reference compensating current is compared with the active filter compensating current extracted from ac system. Thus three phase compensating current Ica, I_{cb} and I_{cc} are produced. The obtained reference current is given to a PWM scheme, which is used to generate controlled gate signal for shunt active filter.

2.3.4 DC bus voltage control

A critical issue in this hybrid active filter is the dc-bus voltage control. The dc bus consists of a single capacitor charged from the power supply. During operation, the active filter may absorb an amount of active power into or release it from the dc capacitor. Excessive active power absorption will increase the dc-bus voltage, and may damage the active filter. The strategy used to control the DC-bus voltage is based on active power control. According to the D–Q theory, a dc component in the D–Q coordinates corresponds to active power. No direct axis current on the D–Q coordinates flows in the LC filter. Thus, the active power is controlled by adjusting the quadrature axis component. The direct axis is set to zero. Figure 2.5 shows a block diagram for the DC bus voltage control.

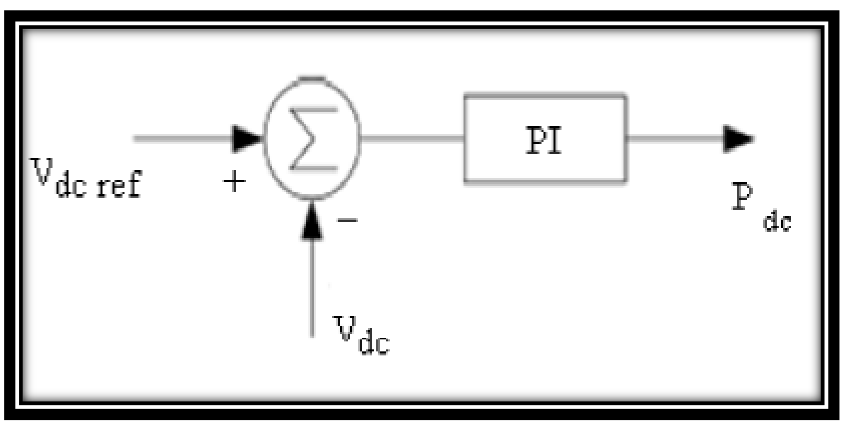

Figure 2.5: Conventional DC link voltage PI controller.

The DC bus voltage is detected and compared with a reference, amplifying the error signal by a control gain of 0.12. A limiter is included in the DC-bus control loop. It is designed to ensure a smooth transient response and to avoid sudden increments or decrements in the DC-bus voltage. It is also designed to prevent the control loop from numerical saturation in the control signals. A DC bus controller is required to regulate the DC bus voltage V_{dc} and to compensate the inverter losses. The measured DC bus voltage V_{dc} of each phase is compared with its reference value V_{dc}*. Similarly, the remaining phases and added all the error signals. The resulting error is applied to a PI regulator. The PWM gate pulses for DSTATCOM are generated by using PWM method.

2.3.5 Conventional DC link voltage controller

Conventional PI Controller is used to maintain the DC Link voltage at the reference value. To maintain the dc-link voltage at the reference at the reference value, the DC Link capacitor needs a certain amount of real power which is proportional to the difference between the actual and reference voltages.

The power required by the capacitor can be expressed as:

$$Pdc = Kp(Vdcref - vdc) + Ki\int(Vdcref - vdc)dt \tag{2.4}$$

The DC-link capacitor has slow dynamics when compared to the compensator. The drawback of this conventional controller is that its transient response is slow, especially for fast-changing loads.

Also, the design of PI Controller parameters is quite difficult for a complex system and hence these parameters are chosen by trial and error. The disadvantage of the conventional PI Controller is the transient response of this controller is very slow.

2.3.6 Fast acting DC link voltage controller

The energy required by the DC Link capacitor to charge from actual value to the reference value can be computed as:

$$Wdc = \frac{1}{2}Cdc(Vdcref^2 - vdc^2) \tag{2.5}$$

In general, the DC-link capacitor voltage has ripples with double frequency with that of the supply frequency.

The DC power required by the dc capacitor can be computed as:

$$Pdc = \frac{Wdc}{Tc} = \frac{1}{2Tc}(Vdcref^2 - vdc^2) \tag{2.6}$$

However due to the lack of integral term there is steady state error while compensating ac and dc loads. This is eliminated by including integral term. The input this controller is error between the squares of reference and actual capacitor voltages. The controller is shown in Figure2.6.

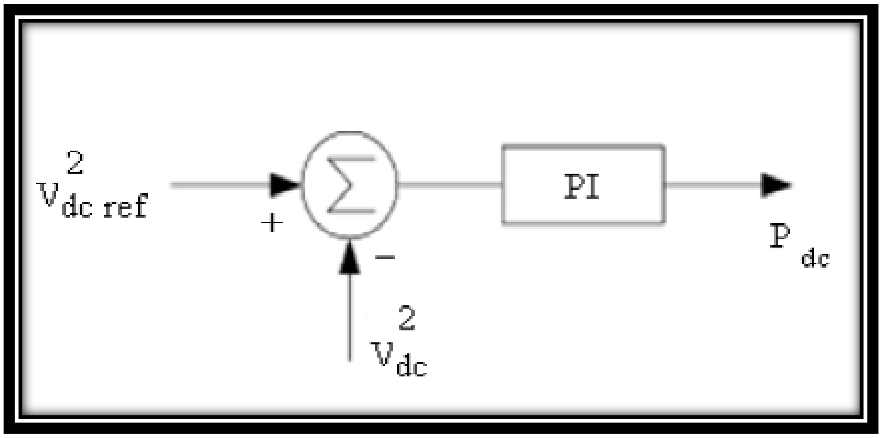

Figure 2.6 Fast acting DC link voltage based PI controller.

An energy based controller it gives fast response compared to the conventional PI controller. The total power required by the DC Link capacitor can be computed as:

$$Pdc = Kpe(Vdc^2 - vdc^2) + Kie\int(Vdc^2 - vdc^2)dt \qquad (2.7)$$

The transient response of the fast acting DC-link voltage controller is very fast when compared to that of the conventional DC Link voltage controller [10].

2.3.4 Applications of D-STATCOM

The applications of the D-STATCOM are:

- Stabilize the voltage of the power grid.
- Reduce the harmonics.
- Increase the transmission capacity.
- Reactive power compensation.
- Power Factor correction [11].

2.4 Fuzzy Logic

The term 'fuzzy' in fuzzy logic was first coined in 1965 by Professor Lofti Zadeh, He used the term 'fuzzy sets' to describe multivalued sets .The entire real world is complex; it is found that the complexity arises from uncertainty in the form of ambiguity. According to Dr. Lotfi Zadeh, principle of compatibility, the complexity, and the imprecision are correlated and ads, the closer one looks at a real world problem, the fuzzier becomes its solution. The Fuzzy Logic tool was introduced in 1965, also by Lotfi Zadeh, and it is a mathematical tool for dealing with uncertainty. It offers to a soft computing partnership the important concept of computing with words. It provides a technique to deal with imprecision and information granularity [2].

2.4.1 Fuzzy sets and fuzzy logic

In classical set theory, a Universe of Discourse (UD) is defined as a collection of objects all having the same characteristics. A classical set is then a collection of a number of those elements. The member elements of a classical set belong to the set 100 per cent. Other elements in the universe of discourse, which are non-member elements of the set, are not related to the set at all. A definitive boundary can be drawn for the set, as depicted in Figure 2.7.

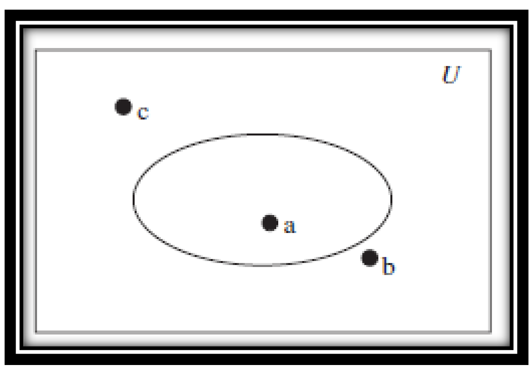

Figure 2.7: Classical/crisp set boundary.

In fuzzy set theory, the concept of characteristic function is extended into a more generalized form, known as membership function: $\mu A(x)$: U $\rightarrow$ [0, 1]. While a characteristic function exists in a two-element set of {0, 1}, a membership function can take up any value between the unit interval [0, 1]. The set which is defined by this extended membership function is called a fuzzy set. The boundary of a fuzzy set is shown in Figure 2.8.

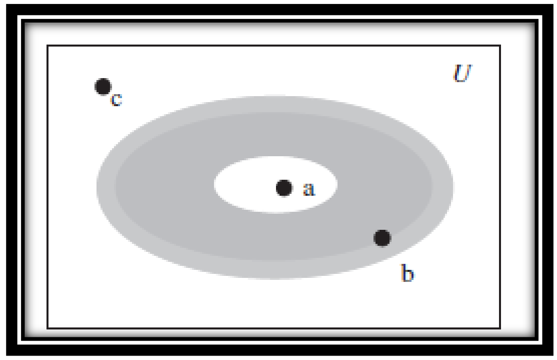

Figure 2.8: Fuzzy set boundary

2.4.2 Types of membership functions

Figure 2.9 shows various types of membership functions which are commonly used in fuzzy set theory.

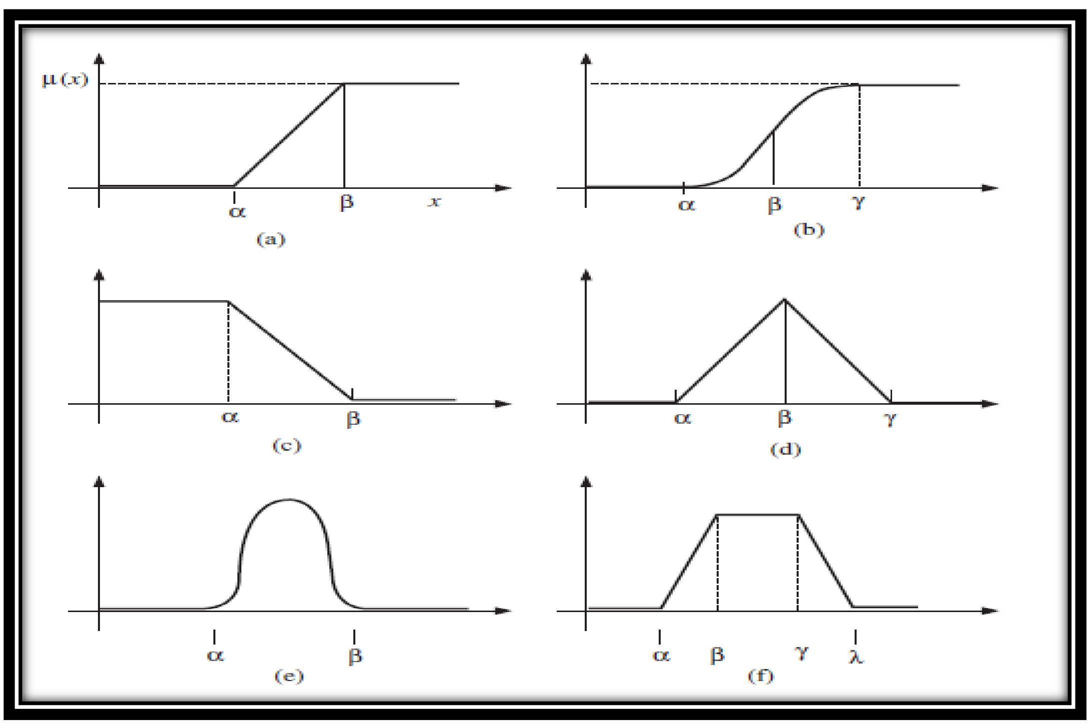

Figure 2.9: Types of membership functions: (a) Γ-function (b) S-function(c) L-function; (d) Λ-function (e) Gaussian function (f) Π-function.

The choice of shape depends on the individual application. In fuzzy control applications, Gaussian or bell-shaped functions and S-functions are not normally used. Functions such as Γ-function, L-function and Λ-function are far more common.

2.4.3 Linguistic variables

The concept of a linguistic variable, a term which is later used to describe the inputs and outputs of the Fuzzy Logic Controller (FLC), is the foundation of fuzzy logic control systems. A conventional variable is numerical and precise. It is not capable of supporting the vagueness in fuzzy set theory. By definition, a linguistic variable is made up of words, sentences or artificial language which is less precise than numbers. It provides the means of approximate characterization of complex or ill-defined phenomena [12].

2.4.4 Fuzzy control systems

Figure 2.10 shows the block diagram of a typical Fuzzy Logic Controller (FLC).

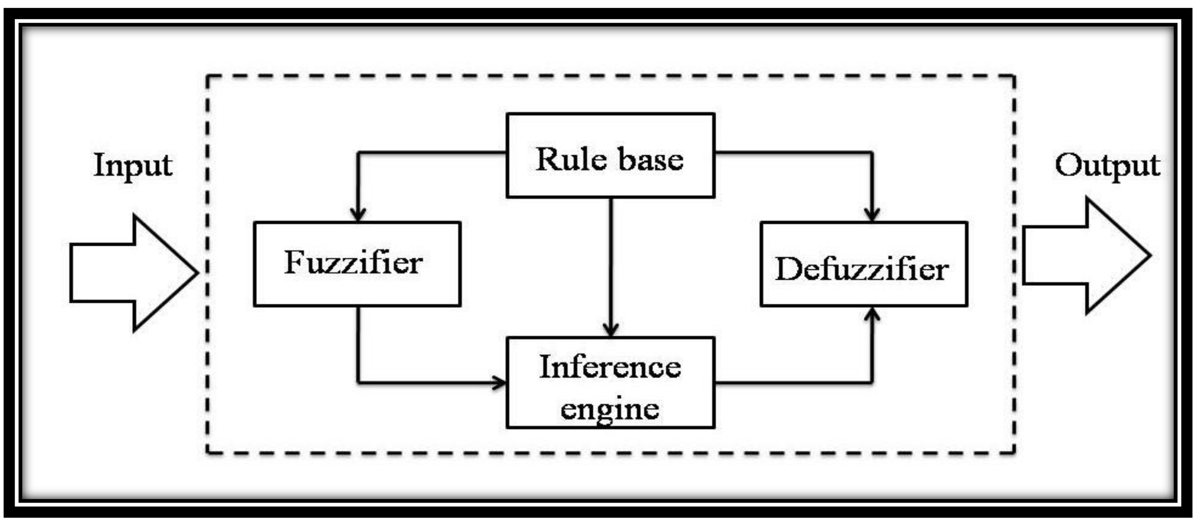

Figure 2.10: A fuzzy logic system

There are five principal elements to a fuzzy logic controller:

- Fuzzification module (fuzzifier).
- Knowledge base.
- Rule base.
- Inference engine.
- Defuzzification module (defuzzifier).

2.4.5 Fuzzification

The operations in fuzzy logic are performed in terms of fuzzy sets. In practice, the input data may also be in terms of fuzzy sets or a singleton (single element with a membership value of unity), which is in fact a special type of fuzzy set. The input data needs to be assigned membership values of one or more fuzzy sets into which the Universe of Discourse (UD) has been partitioned. The membership values are found from the intersections of the data sets with the fuzzy sets of the UD. For the singleton in figure 2.9(a), there are two intercepts, i.e., at a and b, which determine the membership values. Whilst for the fuzzy input in Figure 2.11(b) there are four intercepts at c, d, e and f which determine the membership values.

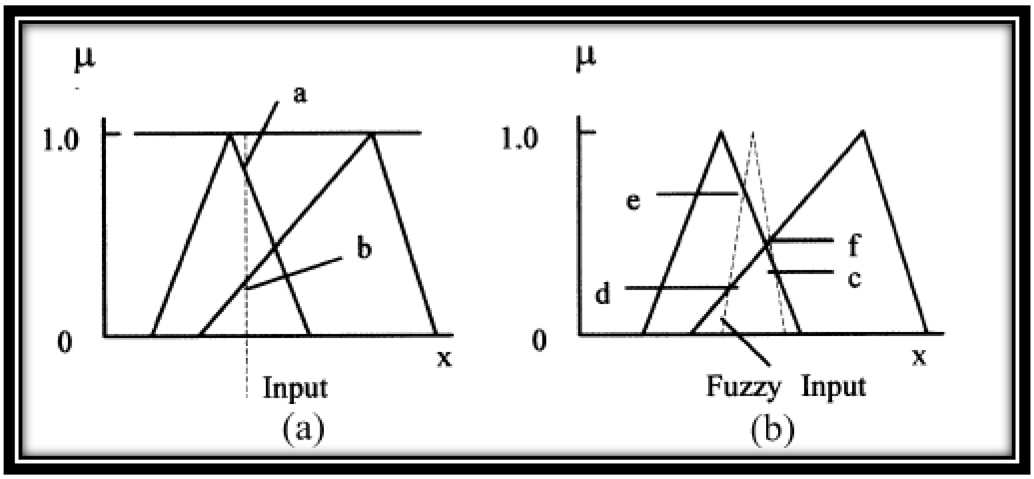

Figure 2.11: Assigning input data membership values. (a) Singleton input. (b) More general fuzzy input.

2.4.6 Defuzzification

This means the reduction of the fuzzy set or subset to a singleton. The fuzzy set is usually the union of several subsets representing the conclusion of a fuzzy proposition. Normally, a fuzzy set cannot be represented by a singleton; therefore defuzzification can only be undertaken with the loss of information. The union of several subnormal (no membership value equal to unity) fuzzy subsets is illustrated in Figure 2.12 and s is the single element on the UD which is deemed to represent the union of the fuzzy subsets.

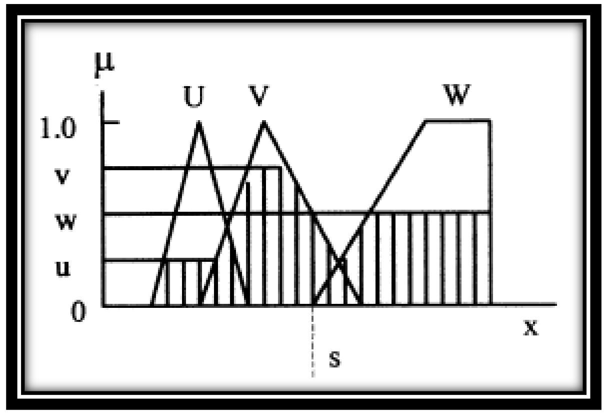

Figure 2.12: The union of several fuzzy subsets

Such a representation discards the span of the conclusion and the membership values of the subsets. But for calculations in design (for example) a specific value is required and provides the motivation for defuzzifying, but it is important not to lose sight of the whole solution.

There are several ways of finding a representative number. Two common ways are outlined below.

(i) Centroid method

This is probably the most frequently used method and as the name suggests, it involves finding the position of the centre of area of the subsets on the abscissa (s).

Continuous distribution:

$$s = \int_{x=0}^{x=\infty} x\, da / \int da \tag{2.8}$$

Discrete distribution:

$$s = \sum_{i=1}^{i=n} xi \quad \delta Ai / \sum \delta Ai \tag{2.9}$$

(ii) Weighted abscissa method

This is evaluated by taking the sum of the normalized weighting of each of the set principal values, xi (max).

$$s = \sum_{i=1}^{i=n} Mi\ xi\ (\max) / \sum \mu i \tag{2.10}$$

In the trapezoidal shape of fuzzy set, it is the mid-support value that is used for xi. The centroid and weighted abscissa methods generally give somewhat different values of the defuzzified representative number. It may be observed that given a representative number, it is generally not possible to recover the original fuzzy subset [13].

2.4.7 Fuzzy logic implication

Fuzzy implication is an important connective in fuzzy control systems because the control strategies are embodied by sets of IF-THEN rules. There are various different techniques in which fuzzy implication may be defined. These relationships are mostly derived from multi valued logic theory. The following are some of the common techniques of fuzzy implication:

- **Mamdani:** This method is widely accepted for capturing expert knowledge. It allows us to describe the expertise in more intuitive, more humanlike manner. However, Mamdani type Fuzzy Inference System (FIS) entails a substantial computational burden.
- **Takagi-Sugeno:** This method is computationally efficient and works well with optimization and adaptive techniques, which makes it very attractive in control problems particularly for dynamic nonlinear systems. These adaptive techniques can be used to customize the membership functions so that fuzzy system best models the data.

The most fundamental difference between Mamdani type FIS and Sugeno type FIS is the way the crisp output is generated from the fuzzy inputs. While Mamdani type FIS uses the technique of defuzzification of a fuzzy output Sugeno type FIS uses weighted average to compute the crisp output. The expressive power and interpretability of Mamdani output is lost in the Sugeno FIS since the consequents of the rules are not fuzzy. But Sugeno has better processing time since the weighted average replace the time consuming defuzzification process. Due to the interpretable and intuitive nature of the rule base Mamdani type FIS is widely used in particular for decision support application. Other differences are that Mamdani FIS has output membership functions whereas Sugeno FIS has no output membership functions. Mamdani FIS is less flexible in system design in comparison to Sugeno FIS as latter can be integrated with Adaptive Neuro Fuzzy Inference System (ANFIS) tool to optimize the outputs [14].

CHAPTER THREE

DSTATCOM MODELING AND CONTROL

3.1 Modeling of DSTATCOM

Figure3.1 shows the Simulink model of DSTATCOM which consists of two Voltage Source Converters (VSC) connected in cascaded form by a DC link which acts as a voltage source for the two inverters. In the average model of a Distribution STATCOM, the IGBT Voltage-Sourced Converters (VSC) are represented by equivalent voltage sources generating the AC voltage averaged over one cycle of the switching frequency. This model does not represent harmonics, but the dynamics resulting from the control system and power system interaction are preserved. This model allows using much larger time steps (typically 40-50 microseconds), thus allowing simulations of several seconds.

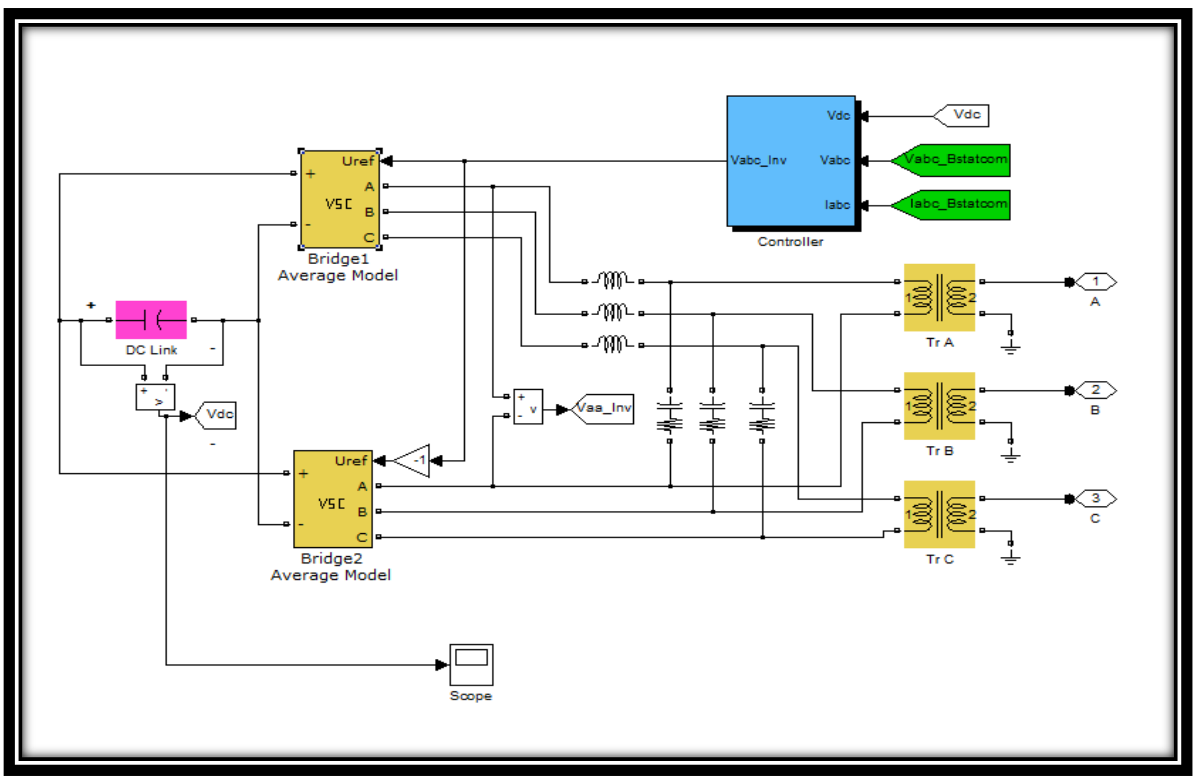

Figure 3.1: The Simulink model of DSTATCOM

3.2 Fuzzy Logic Based Supervision of DC Link PI Control

A fuzzy logic based supervisor control is designed to manipulate the gains of PI controller employed for DC link voltage control. The fuzzy supervisor is designed in such a way that the gains generated by the fuzzy supervisor which are added to the reference proportional and integral gains are able to maintain the DC Link voltage fairly constant so that voltage regulation is done satisfactorily. Figure 3.2 shows the fuzzy supervisor implemented for DC link PI control.

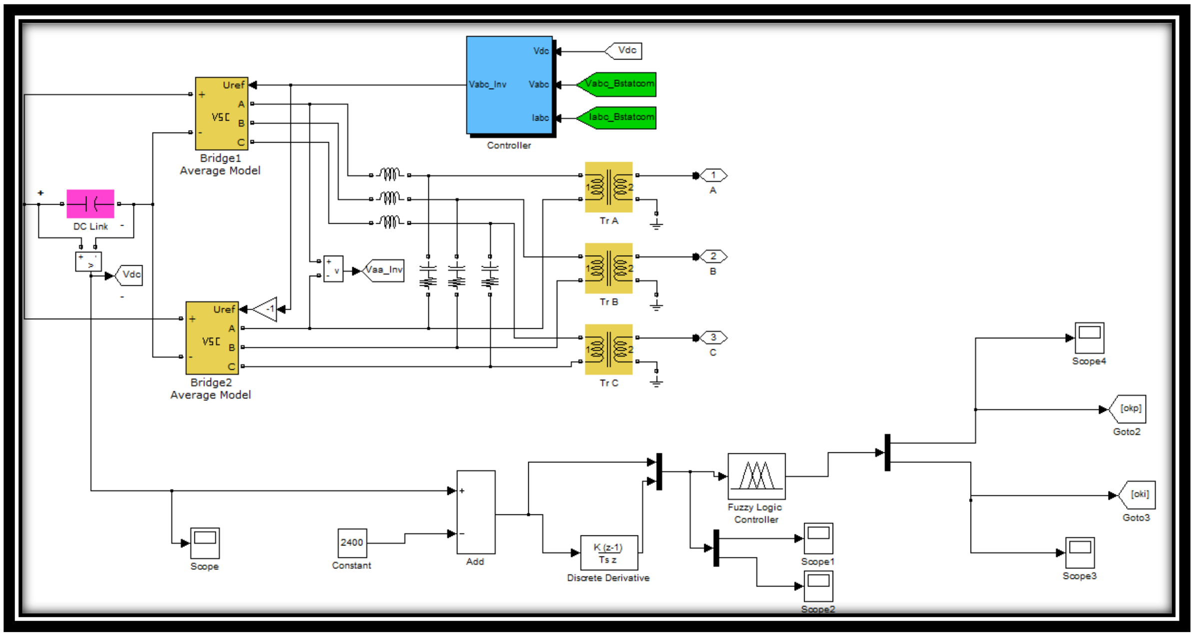

Figure 3.2: Fuzzy logic control implemented for DC link

3.3.1. Inputs and outputs

The inputs of the fuzzy supervisor have been chosen as the error in DC link voltage and the change in error in DC link voltage. The outputs of the fuzzy supervisor are chosen as the change in K_p value and the change in K_i value. The two inputs to the fuzzy controller are error and change in error, and the two outputs DK_p and DK_i are shown in the Figure 3.3.

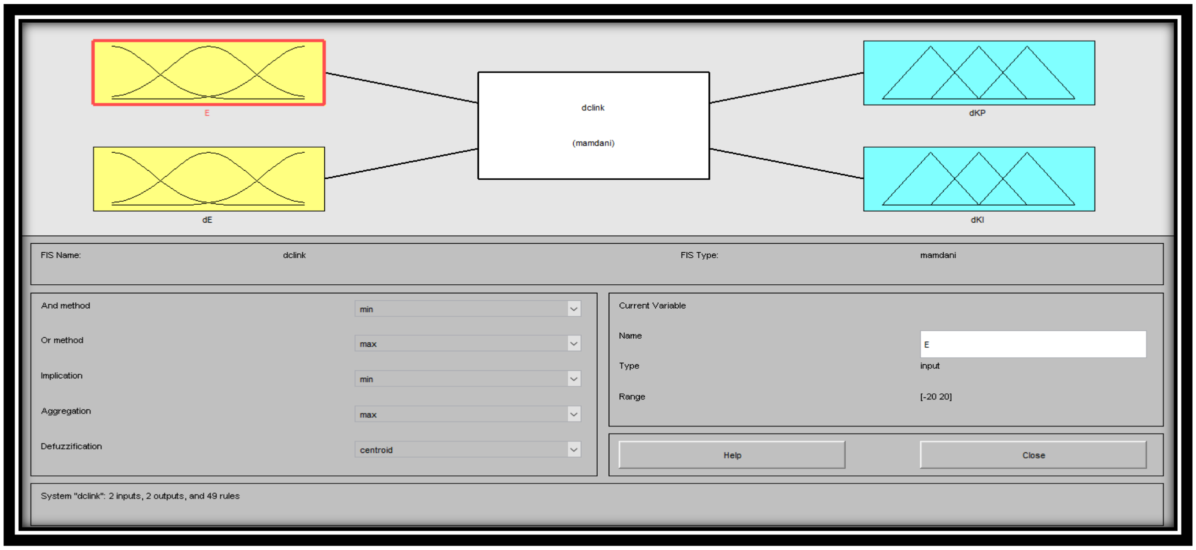

Figure 3.3: MATLAB Fuzzy logic controller

3.3.2 System fuzzification

Seven triangular membership functions have been chosen: Negative Large (NL), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM) and Positive Large (PL) for both error (err) and change in error (derr). The input membership functions are shown in Figure 3.4.

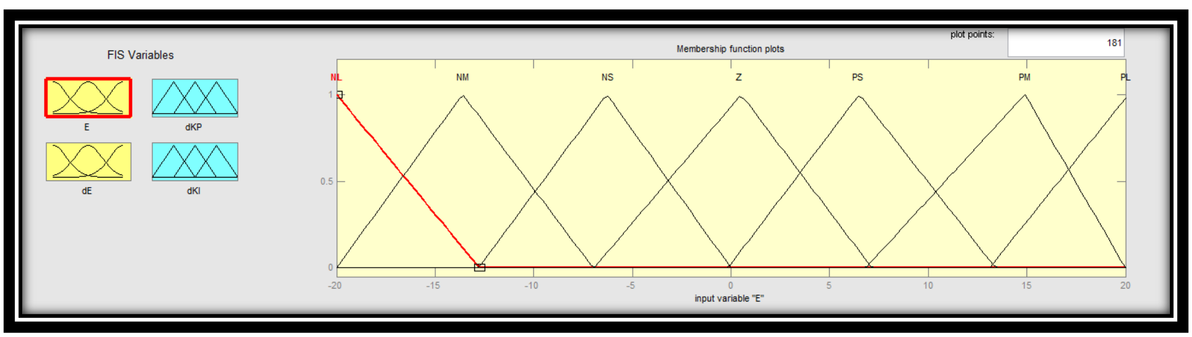

Figure 3.4(a): Membership functions for error input

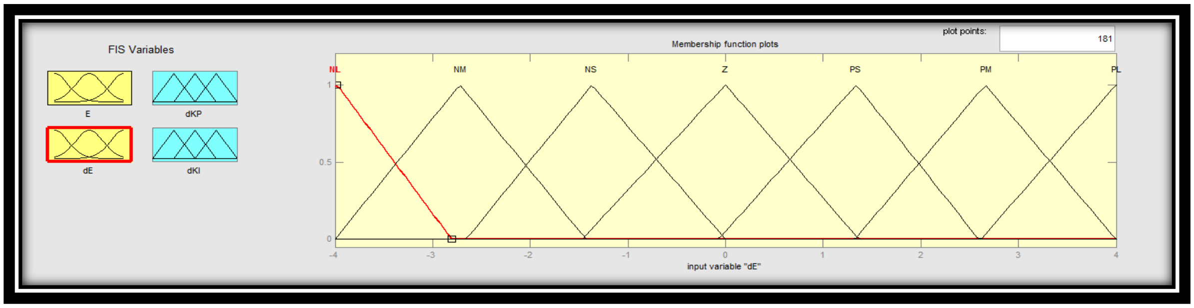

Figure 3.4(b)**:** Membership functions for change in error

The membership functions for DK_p and DK_i are as shown in Figure 3.5.

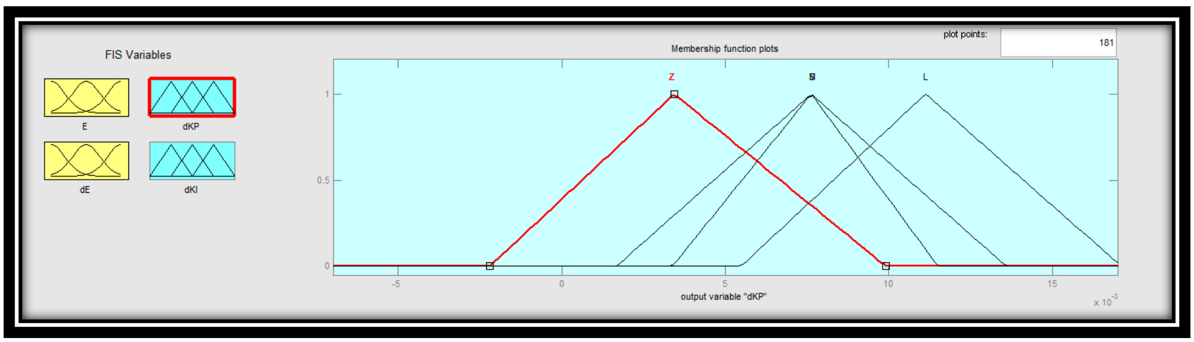

Figure 3.5 (a): Output membership functions for DK_p

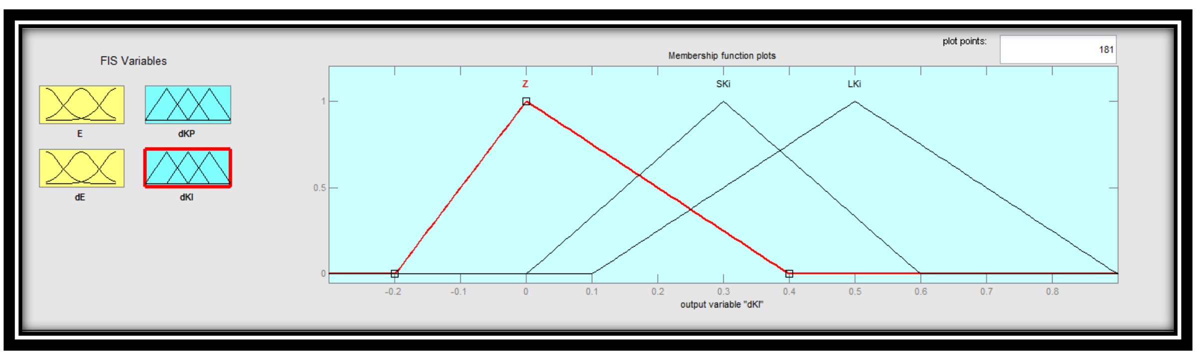

Figure 3.5(b)**:** Output membership functions for DK_i

3.3.4 The rule base

In this study there are forty nine rules for change in K_p and forty nine rules for change in K_i.

Some rules for change in K_P are:

If err is NL and derr is NL then DK_P is L

If err is NL and derr is NM then DK_P is L

If err is NL and derr is NS then DK_P is L

If err is NL and derr is Z then DK_P is M

The whole control rules for change in K_p are shown in Table 3.1.

Table 3.1: Rule base for change in K_p

error / derr	**NL**	**NM**	**NS**	**Z**	**PS**	**PM**	**PL**
NL	L	L	L	M	S	S	Z
NM	L	L	M	S	S	Z	S
NS	L	M	S	S	Z	Z	Z
Z	M	Z	Z	Z	Z	Z	M
PS	Z	Z	Z	S	S	M	L
PM	S	Z	S	S	M	L	L
PL	Z	S	S	M	L	L	L

Some rules for change in K_i are:

If err is NL and derr is NL then DK_i is SK_i

If err is NL and derr is NM then DK_i is Sk_i

If err is NL and derr is NS then DK_i is Sk_i

If err is NL and derr is Z then DK_i is Z

The whole control rules for change in K_i are shown in Table 3.2.

Table 3.2: Rule base for change in K_i

error / derr	**NL**	**NM**	**NS**	**Z**	**PS**	**PM**	**PL**
NL	SK_i	SK_i	SK_i	Z	Z	Z	Z
NM	SK_i	SK_i	SK_i	Z	Z	Z	Z
NS	LK_i	LK_i	LK_i	Z	Z	Z	Z
Z	LK_i	LK_i	LK_i	Z	LK_i	LK_i	LK_i
PS	Z	Z	Z	Z	LK_i	LK_i	LK_i
PM	Z	Z	Z	Z	SK_i	SK_i	SK_i
PL	Z	Z	Z	Z	SK_i	SK_i	SK_i

3.3.5 Rule editor

Based on the descriptions of the input and output variables defined with the FIS editor, the rule editor allows to construct the rule statements automatically, by clicking on and selecting one item in each input variable box, one item in each output box, and one connection item. Rules may be changed, deleted or added by clicking on the appropriate button. The rule editor shown in Figure 3.6 used to provide rules for all possible combinations of the membership function for error and change in error.

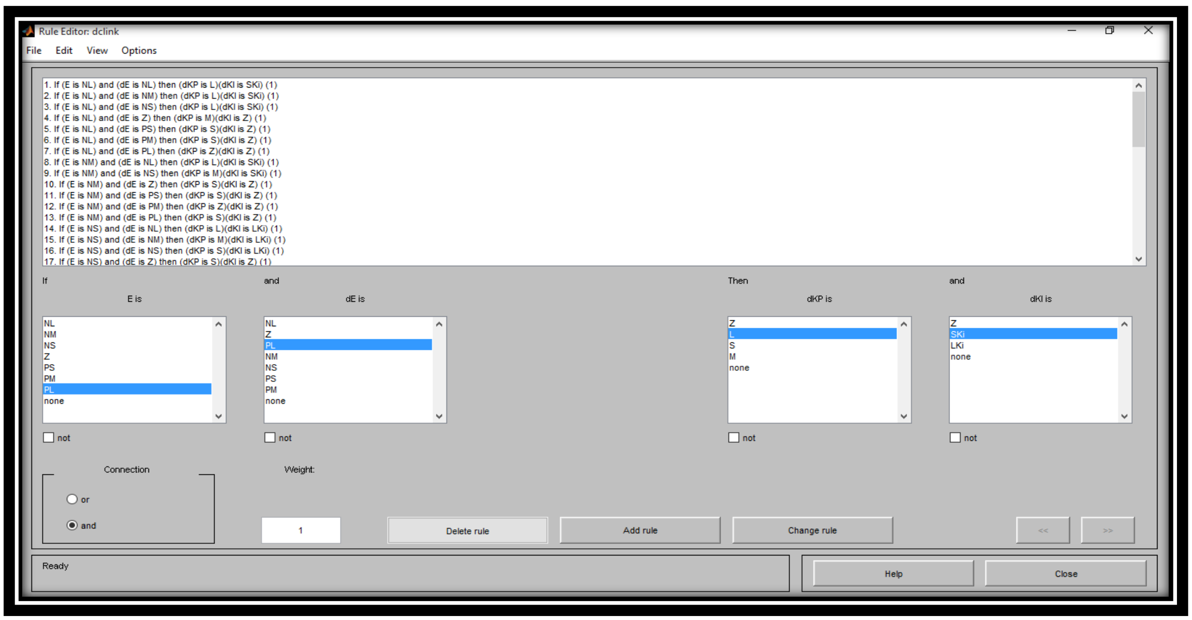

Figure 3.6: MATLAB rule editor

The surface viewer of above rules is shown in Figure 3.7.

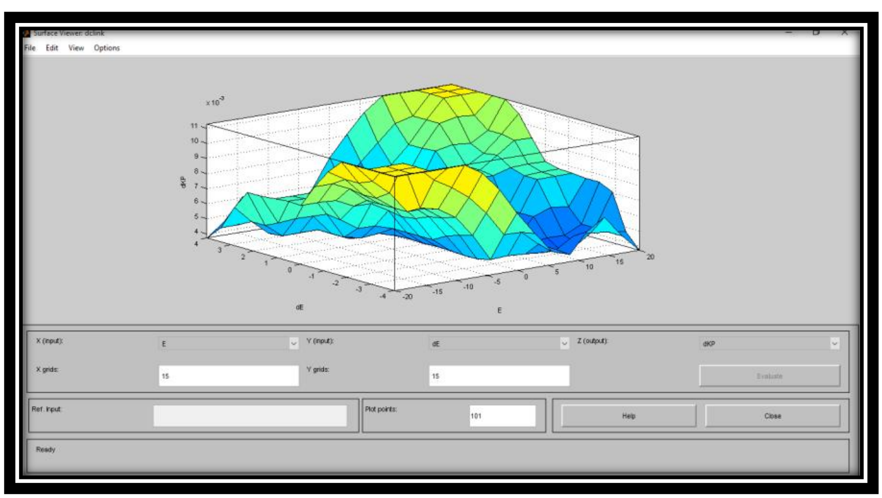

Figure 3.7: Surface viewer

3.3.6 Defuzzification

There is several methods for defuzzification , the center of gravity method has been used in this work because in this method, the resultant crisp output is sensitive to all of the active fuzzy outputs of the inference mechanism.

Figure 3.8 shows the PI controller with inputs from DC link voltage with fuzzy logic supervisor.

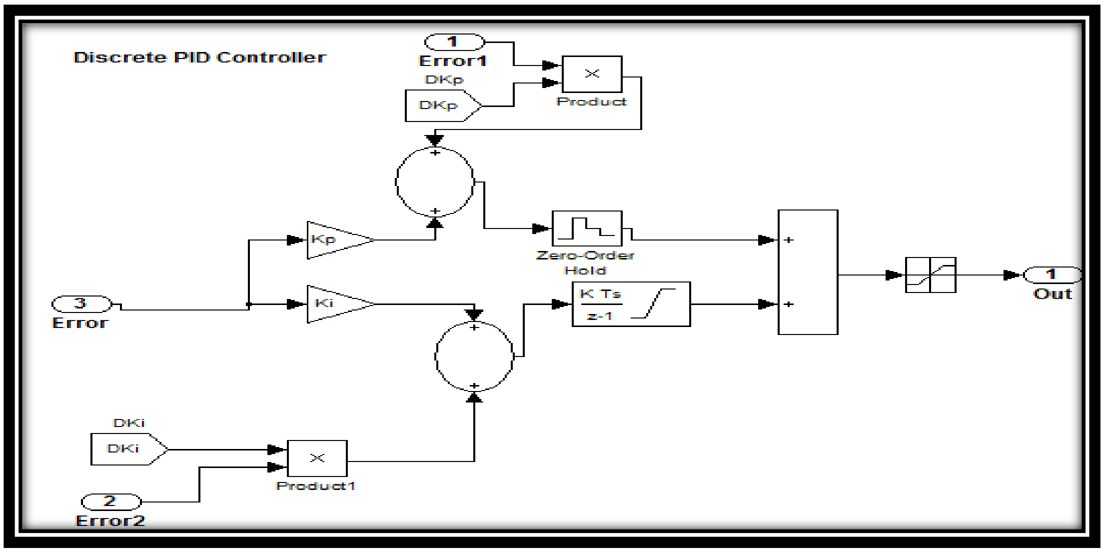

Figure 3.8: PI controller with fuzzy logic supervisor

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Introduction

The test system shown in Figure 4.1 comprises of 25kV, 100 MVA, 50Hz system feeding a distribution network of 600V through a 25kV transmission network. The transmission network comprises of 3 buses. Between B1 and B2 a 21KM feeder of R=0.1153 Ohm/KM and L=1.048e-3 H/KM is connected. Between B2 and B3 a 2Km feeder and a RC load of 3MW and 0.2MVAR are connected. At Bus-3, 25kV/600V, 6MVA transformer is connected to which a variable load of 3000A, 0.9pf and a nonlinear load comprising of a 3-Phase full wave rectifier with a power load of 10KW and 10KVAR are connected. In this chapter the above test system was implemented in MATLAB /Simulink. This section is divided into three cases. First case system without DSTATCOM, second case system with DSTATCOM Voltage controller and third case DSTATCOM voltage controller with Fuzzy logic based supervision of DC Link PI control. Then the simulation results for the DC link voltage for second case without Fuzzy supervision and third case with fuzzy supervision were compared.

4.2 System without DSTATCOM

Figure 4.1 shows the MATLAB model for the system without DSTATCOM.

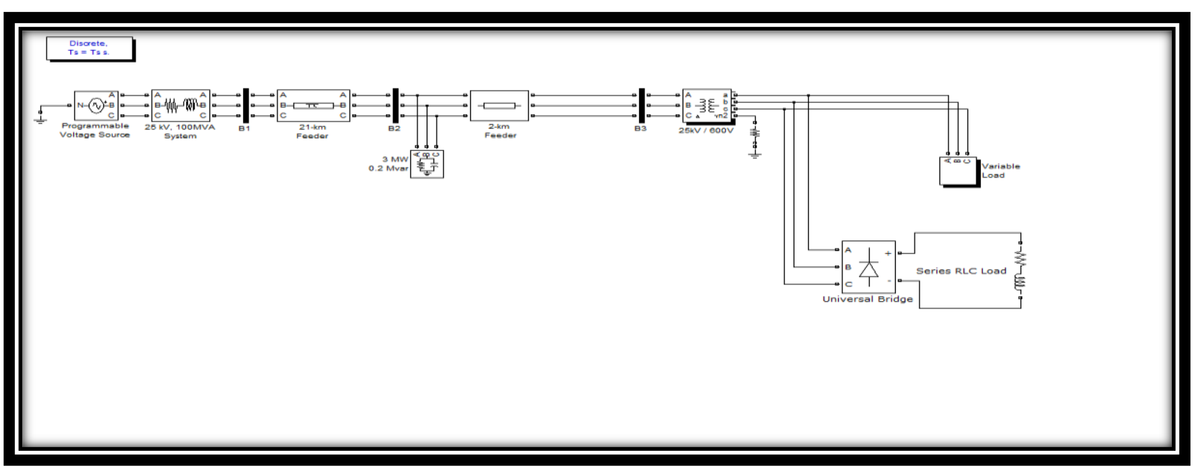

Figure 4.1: MATLAB/Simulink model without DSTATCOM

Figure 4.2 shows three phase voltage in pu at Bus-3 without DSTATCOM using programmable voltage source with a voltage swell of 1.077 pu created at .4 seconds.

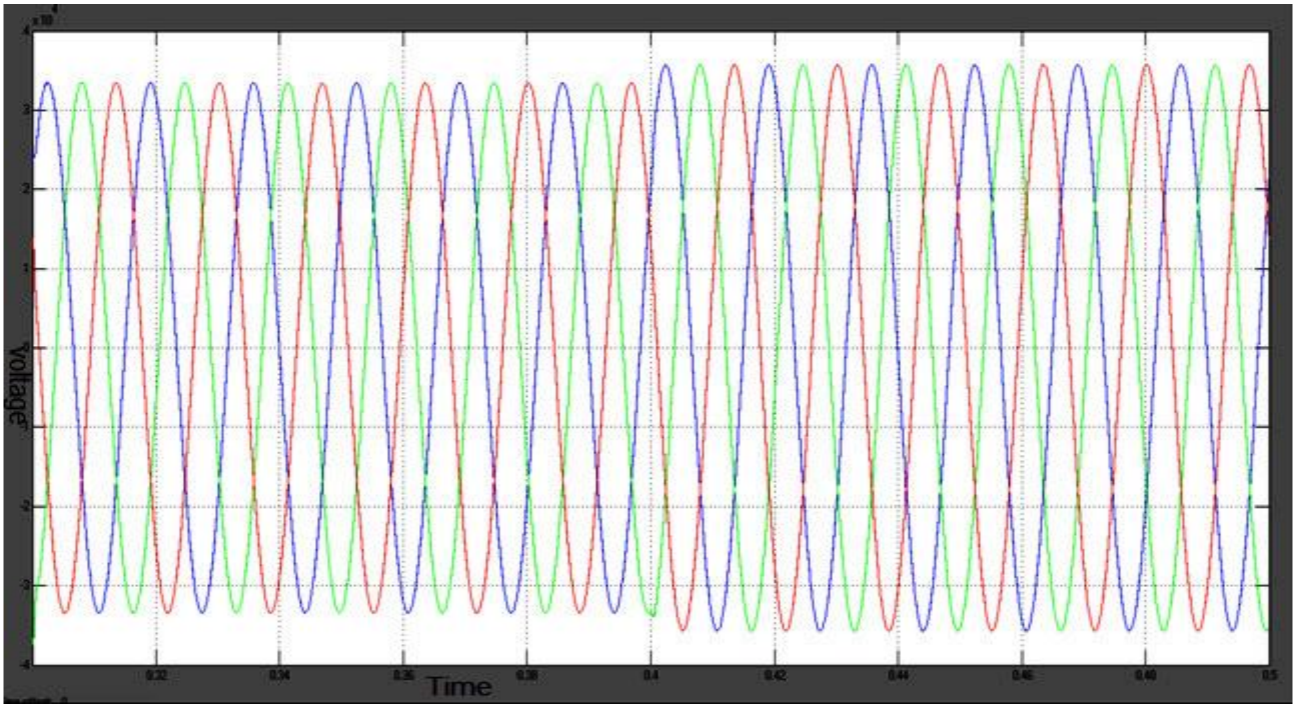

Figure 4.2 Three phase Voltage in Pu at Bus-3 without DSTATCOM

4.3 System with DSTATCOM Voltage Controller

As shown in Figure 4.3 DSTATCOM is connected to Bus-3 through 1.25/25 kV Linear transformers. The compensation capacity of DSTATCOM is +/- 3 MVAR and the voltage level of DC link is 2400V. The capacitance of DC link is 10000μF.

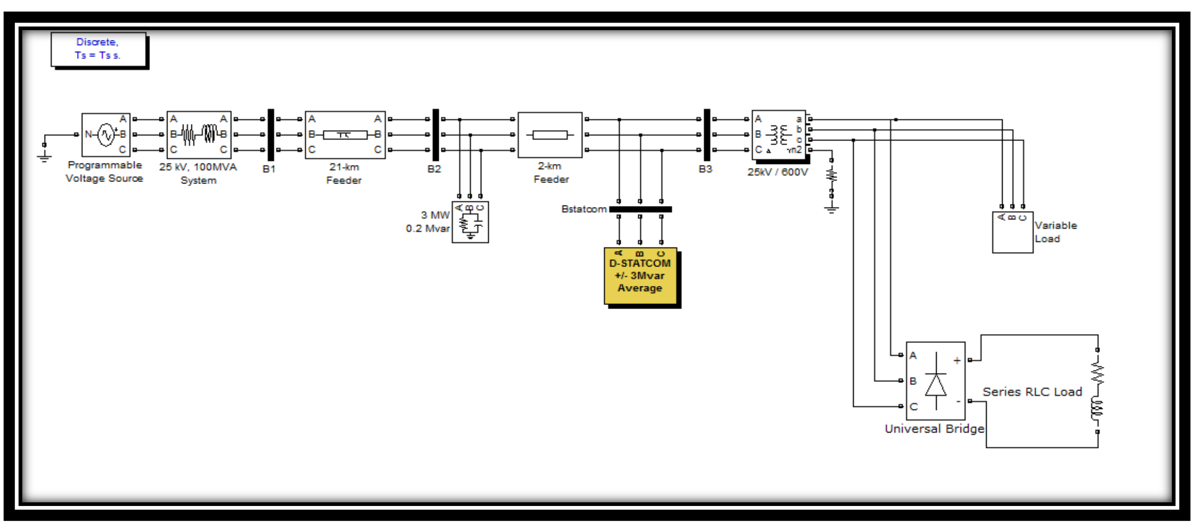

Figure 4.3: Simulink model with DSTATCOM

Figure 4.4 shows the load voltage wave forms in case of connecting DSTATCOM.

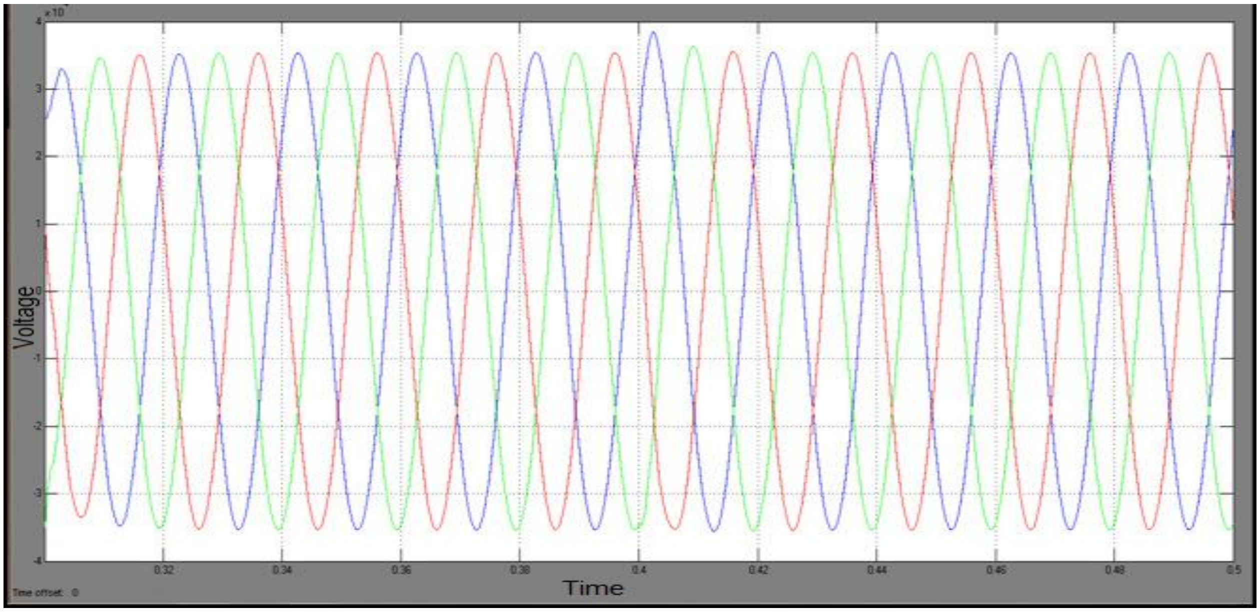

Figure 4.4: Load Voltage (PCC voltage) waveforms with DSTATCOM

There is a considerable variation I the DC link voltage due to sudden voltage swell created at .4 seconds as shown in Figure 4.5.

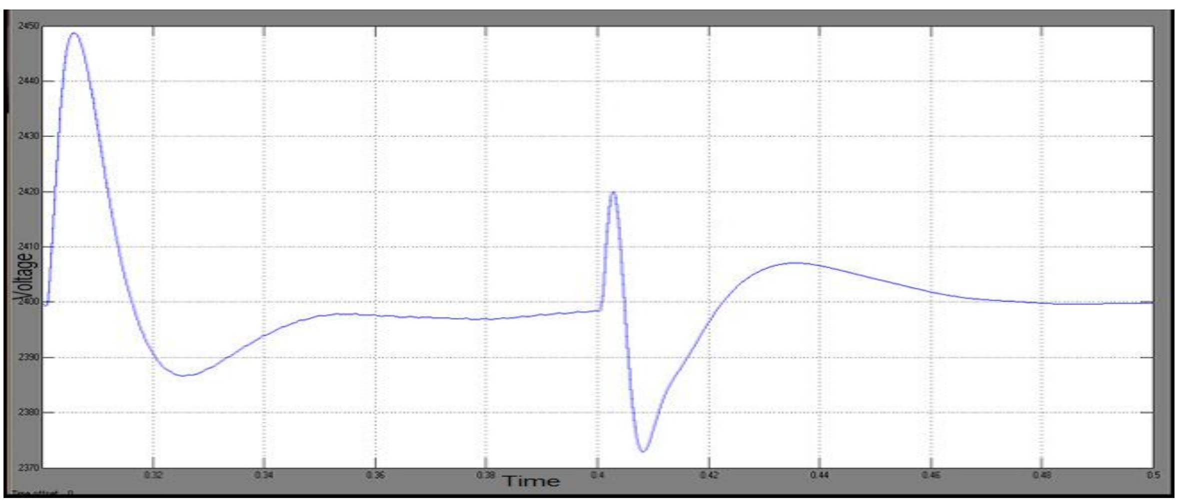

Figure 4.5: DC Link voltage of DSTATCOM

4.4 Fuzzy Logic Based Supervision of DC Link PI Control

The defuzzified outputs of fuzzy logic supervisor DK_p and DK_i values at each and every instant of time are as shown in Figure 4.6.

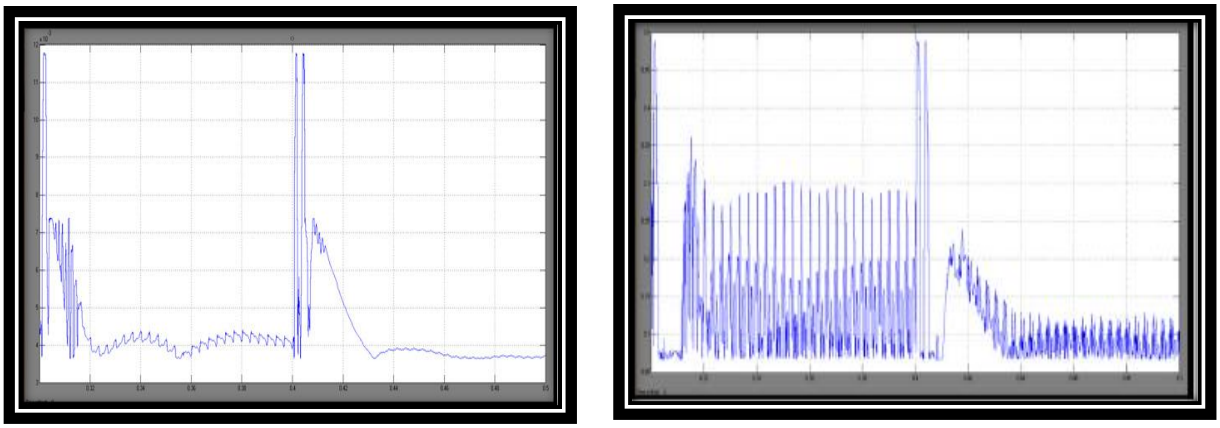

Figure 4.6: Defuzzified outputs of DK_p and DK_i

Figure 4.7 shows the DC link voltage after adding the fuzzy controller.

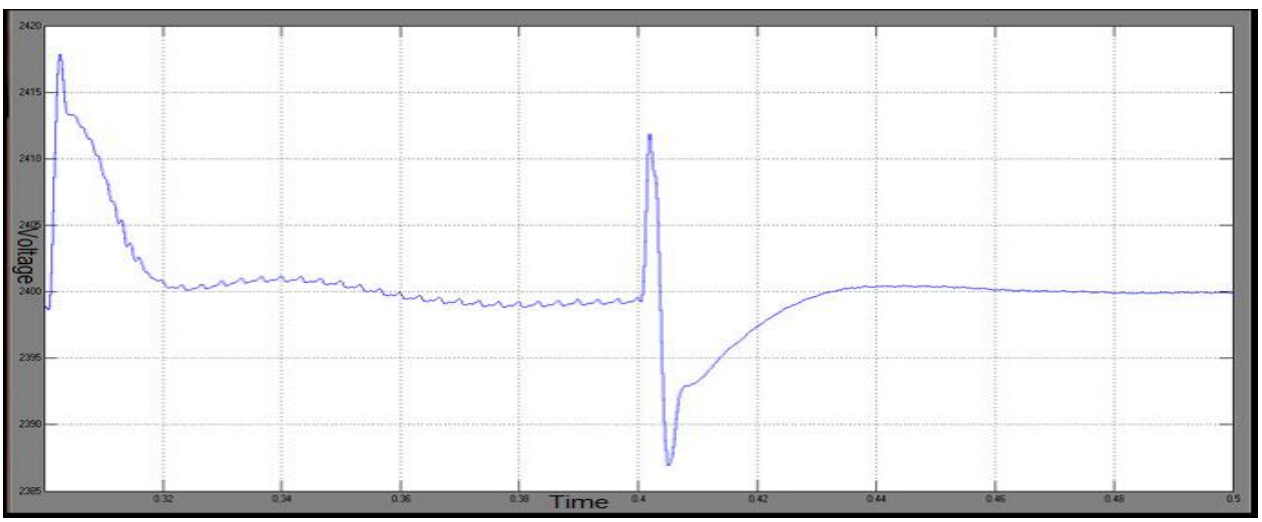

Figure 4.7: DC link voltage with fuzzy design

The improved load voltage with implementation of fuzzy supervision is shown in Figure 4.8.

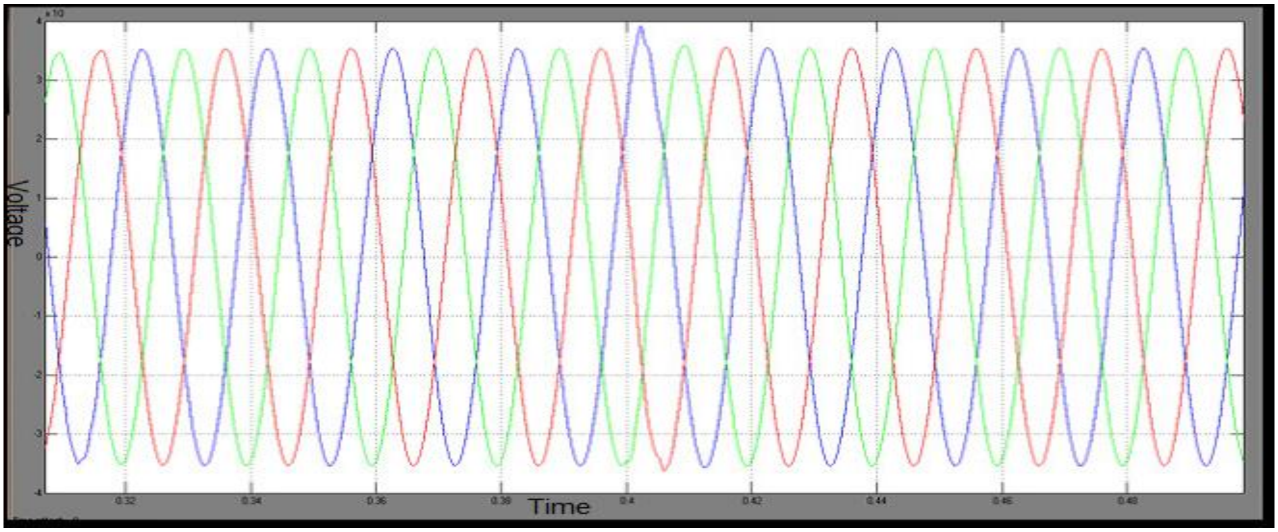

Figure 4.8**:** Load voltages at PCC with fuzzy supervision of DC Link PI control

Table 4.1: System characteristics before and after adding the FLC

	Before adding the FLC	After adding the FLC
Voltage deviation	8 volts	4 volts
Settling time	0.48 second	0.44 second

By comparing the DC link voltages without Fuzzy supervision and with Fuzzy supervision we find that there is reduction in the error in DC link capacitor voltage compared to a normal PI controller is obtained and also voltage waveform has a faster settling time.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

A fuzzy logic supervisory control to of DC link PI controller in a D-STATCOM has been proposed. The supervisor varies the gain of the PI controller during the transient period in a way that improves the system performance. The system has been modeled and simulated in the MATLAB technical environment with a case study. The performance of the DC link voltage was observed with and without fuzzy supervisor.

Simulation results show that a 50-60% reduction in voltage deviation of the DC link voltage is obtained with faster settling time .Good compensation has been observed. Thus, through simulation studies, the implementation of a fuzzy supervisor for DC link voltage control in DSTATCOM for load compensation has been demonstrated.

5.2 Recommendations

- To propose a control strategy, where the optimum values of the PI controller parameters are tuned by hybrid control algorithm.
- To model and control D-STATCOM with Sugeno Fuzzy Controller (SFC).

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