Abstract— Fuzzy logic based controllers have been designed for controlling a STATCOM in a multimachine power system. Such controllers do not need any prior knowledge of the plant to be controlled and can efficiently control a STATCOM during different disturbances in the network. Two different approaches for the controller are mainly used: one is conventional controller using PI design and other one is fuzzy logic design based on membership functions. Review is based on simulation results, along with a comparison of the conventional PI controller performance with that of the fuzzy logic controller will be presented. Thus the several advantages of FLC based intelligence controlled STATCOM serves as the most reliable system for our future power transmission.

Keywords— STATCOM, Multimachine, Fuzzy Logic Controller, 9-Bus System, Reactive Power Control

I. INTRODUCTION

Power Generation and Transmission is a complex process, requiring the working of many components of the power system in tandem to maximize the output. One of the main components to form a major part is the reactive power in the system. It is required to maintain the voltage to deliver the active power through the lines. Loads like motor loads and other loads require reactive power for their operation. To improve the performance of ac power systems, we need to manage this reactive power in an efficient way and this is known as reactive power compensation. There are two aspects to the problem of reactive power compensation: load compensation and voltage support. Load compensation consists of improvement in power factor, balancing of real power drawn from the supply, better voltage regulation, etc. of large fluctuating loads. Voltage support consists of reduction of voltage fluctuation at a given terminal of the transmission line. Two types of compensation can be used: series and shunt compensation. These modify the parameters of the system to give enhanced VAR compensation. In recent years, static VAR compensators like the STATCOM have been developed. These quite satisfactorily do the job of absorbing or generating reactive power with a faster time response and come under Flexible AC Transmission Systems (FACTS). This allows an increase in transfer of apparent power through a transmission line, and much better stability by the adjustment of parameters that govern the power system i.e. current, voltage, phase angle, frequency and impedance. Controlling of STATCOM can be done by using fuzzy logic. Fuzzy logic is used instead of conventional method because it can be operated under uncertain condition. Today’s changing electric power system creates a growing need for reliability, flexibility, fast response and accuracy. FACTS are new devices emerging from recent innovative technologies that are capable of altering voltage phase angle and/or impedance at particular points in power system.

Objective of the project is to control the reactive power of multi machine system using fuzzy logic base STATCOM. Fuzzy logic control is used to remove the problem of uncertainty and non-linearity in power system. Fuzzy logic based controller’s output is compared with the conventional PI controller’s output in MATLAB. The main focus of the research in fuzzy logic is on the development of intelligent controllers for reactive power and voltage regulation. Currently, research is done in progress on fuzzy logic and genetic algorithm techniques to improve load balancing within a distributed system.

II. LITERATURE SURVEY

In 1998- Chun Li et al designed a STATCOM to supply fast voltage control and to enhance the damping of inter-area electromechanical oscillations of the system. By investigating the added synchronizing and damping torque induced by STATCOM, the conflicts between these control objectives were analysed and the limitations or even invalidity of the fixed-parameters damping controller for certain system parameters and load conditions was discussed. A rule-based controller, which employs bang-bang, fuzzy logic or fixed-parameter PI control strategy according to the operation state of the system, was designed. The advantages of the proposed controller over the fixed-parameter PI controller were demonstrated by nonlinear digital simulations. [1]

In 2000- L.O. Mak et al designed the fuzzy controller for static synchronous compensator (STATCOM) to enhance interconnected power system stability. The power frequency model for STATCOM with conventional controllers was presented first. Fuzzy controllers were then designed for both main and supplementary controllers of the STATCOM. The fuzzy main control was constant voltage control with voltage regulation which aims at providing voltage support on the tie lines of interconnected power systems to enhance transient stability and increase transfer limit.
The fuzzy supplementary control (SC) was designed for damping inter-area power oscillation and enhancing dynamic stability of interconnected power systems. The integrated STATCOM model had been incorporated to the small signal stability and transient stability programs with a novel interface. Computer tests were conducted on a four-generator test system. The results show that STATCOM can enhance system transfer limit and improve system dynamic behavior significantly. Computer results also show that the performance of fuzzy controllers was fairly well and possesses good robustness. [2]

In 2001- Pierre Giroux et al designed the model of a STATCOM (Static Synchronous Compensator) used for reactive power compensation on a distribution network. An “average modelling” approach was proposed to simplify the PWM inverter operation and to accelerate the simulation for control parameters adjusting purpose. Simulation performance obtained with both modelling approaches were presented and compared. Two modeling approaches (device and average modeling) have been presented and applied to the case of a +3Mvar D-STATCOM connected to a 25-kV distribution network. The obtained simulation results have demonstrated the validity of the developed models. Average modeling allows a faster simulation which is well suited to controller tuning purposes. [3]

In 2003- Stella Morris et al presented two new variable structure fuzzy control algorithms for controlling the reactive component of the STATCOM current in a power system. The control signal was obtained from a combination of generator speed deviation and STATCOM bus voltage deviation fed to the variable structure fuzzy controller. The parameters of these fuzzy controllers can be varied widely by a suitable choice of membership functions and parameters in the rule base. Simulation results for typical single machine and multimachine power systems subject to a wide range of operating condition changes confirm the efficiency of the new controllers. [4]

In 2004- Salman Mohagheghi et al designed a Takagi-Sugeno (TS) based fuzzy logic controllers for controlling a STATCOM in a multimachine power system. The first two controllers are simulated and the results show better and faster damping compared to that of the conventional PI controller. Even though both conventional and SSMF fuzzy controllers designed and simulated in this work, tend to rely on the fuzzy inference and reasoning, they still slightly depend on the nature of the plant. In other words, a better knowledge of the dynamics of the STATCOM in this specific power system will lead to a better tuning of the controller, which in turn produces better results at different operating conditions and under various faults applied to the system. [5]

In 2006- A. Ajami et al, investigated application of a role based fuzzy control technique for controlling a STATCOM at steady and transient states. The presented control system has two loops. The first loop is named main controller and regulates the AC bus voltage and damps rotor angle oscillations under steady state and transient conditions. The second control loop is named supplementary controller and regulates the DC capacitor voltage. The presented simulation results show that STATCOM with FLC is capable to enhancing the system transient stability. The simulation results support the applications of fuzzy controllers in power systems. [6]

In 2007- S.V Ravi Kumar and S. Siva Nagaraju described the techniques of correcting the supply voltage sag, swell and interruption in a distributed system. At present, a wide range of very flexible controllers, which capitalize on newly available power electronics components, are emerging for custom power applications. Among these, the distribution static compensator and the dynamic voltage restorer are most effective devices, both of them based on the VSC principle. A DVR injects a voltage in series with the system voltage and a D-STATCOM injects a current into the system to correct the voltage sag, swell and interruption. Comprehensive results are presented to assess the performance of each device as a potential custom power solution. [7]

III. REACTIVE POWER COMPENSATION AND STATCOM

Reactive power is the power that supplies the stored energy in reactive elements. Power, as we know, consists of two components, active and reactive power. The total sum of active and reactive power is called as apparent power. In AC circuits, energy is stored temporarily in inductive and capacitive elements, which results in the periodic reversal of the direction of flow of energy between the source and the load. The average power after the completion of one whole cycle of the AC waveform is the real power, and this is the usable energy of the system and is used to do work, whereas the portion of power flow which is temporarily stored in the form of magnetic or electric fields and flows back and forth in the transmission line due to inductive and capacitive network elements is known as reactive power. This is the unused power which the system has to incur in order to transmit power.

Inductors (reactors) are said to store or absorb reactive power, because they store energy in the form of a magnetic field. Therefore, when a voltage is initially applied across a coil, a magnetic field builds up, and the current reaches the full value after a certain period of time. This in turn causes the current to lag the voltage in phase.

The zero average does not necessarily mean that no energy is flowing, but the actual amount that is flowing for half a cycle in one direction, is coming back in the next half cycle.

The principle of shunt reactive power compensation technique is described below:

**Shunt compensation:**

![Shunt Compensation Diagram]
Fig 3.1 Circuit diagram and phasor diagram of system without any compensation

Fig 3.2 Circuit diagram and phasor diagram with shunt compensation

The figure 3.1 comprises of a source $V_1$, a power line and an inductive load. The figure 3.2 shows the system without any type of compensation. The phasor diagram of these is also shown above. The active current $I_p$ is in phase with the load voltage $V_2$. Here, the load is inductive and hence it requires reactive power for its proper operation and this has to be supplied by the source, thus increasing the current from the generator and through the power lines. Instead of the lines carrying this, if the reactive power can be supplied near the load, the line current can be minimized, reducing the power losses and improving the voltage regulation at the load terminals. This can be done in three ways:

1) A voltage source.
2) A current source.
3) A capacitor.

In this case, a current source device is used to compensate $I_q$, which is the reactive component of the load current. In turn the voltage regulation of the system is improved and the reactive current component from the source is reduced or almost eliminated. This is in case of lagging compensation. For leading compensation, we require an inductor.

Therefore we can see that, a current source or a voltage source can be used for both leading and lagging shunt compensation, the main advantages being the reactive power generated is independent of the voltage at the point of connection.

STATCOM:

One of the many devices under the FACTS family, a STATCOM is a regulating device which can be used to regulate the flow of reactive power in the system independent of other system parameters. STATCOM has no long term energy support on the dc side and it cannot exchange real power with the ac system. In the transmission systems, STATCOMs primarily handle only fundamental reactive power exchange and provide voltage support to buses by modulating bus voltages during dynamic disturbances in order to provide better transient characteristics, improve the transient stability margins and to damp out the system oscillations due to these disturbances.

A STATCOM consists of a three phase inverter (generally a PWM inverter) using SCRs, MOSFETs or IGBTs, a D.C capacitor which provides the D.C voltage for the inverter, a link reactor which links the inverter output to the a.c supply side, filter components to filter out the high frequency components due to the PWM inverter. From the d.c. side capacitor, a three phase voltage is generated by the inverter. This is synchronized with the a.c supply. The link inductor links this voltage to the a.c supply side. This is the basic principle of operation of STATCOM.
For two AC sources which have the same frequency and are connected through a series inductance, the active power flows from the leading source to the lagging source and the reactive power flows from the higher voltage magnitude source to the lower voltage magnitude source. The phase angle difference between the sources determines the active power flow and the voltage magnitude difference between the sources determines the reactive power flow. Thus, a STATCOM can be used to regulate the reactive power flow by changing the magnitude of the VSC voltage with respect to source bus voltage.

The control of the STATCOM voltage magnitude should be such that the specified bus voltage and the STATCOM voltage should be equivalent and there should be no difference between them. By proper design procedure, knowing the limits of the variables and the parameters, but not exactly knowing the power system parameters, simultaneous DC and AC control can be achieved. We can ensure the stability of the power system by the proposed STATCOM controller design. Thus it can work along with the other controllers in the network.

The bus control restraint will be

\[ F = V_p - V_{sp} = 0 \]

\[ V_{sp} \] is the specified voltage.

Control Model for STATCOM:

![Control Scheme of STATCOM]

This is conventional model for STATCOM control. In STATCOM control, pulse generation for thyristors used in STATCOM is most important. So, we designed a pulse generator for controlling purpose.

**IV. FUZZY LOGIC CONTROLLER**

Fuzzy logic is widely used in machine control. The term "fuzzy" refers to the fact that the logic involved can deal with concepts that cannot be expressed as "true" or "false" but rather as "partially true". Although alternative approaches such as genetic algorithms and neural networks can perform just as well as fuzzy logic in many cases, fuzzy logic has the advantage that the solution to the problem can be cast in terms that human operators can understand, so that their experience can be used in the design of the controller. This makes it easier to mechanize tasks that are already successfully performed by humans.

![Block Diagram of Fuzzy Logic Controller]

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V. CASE STUDIES

Due to the load variation and faults, power system always suffers from voltage sag. This due to the fact that increased load draws more reactive current from source and reactive power is proportional to bus voltage. So when load draws more current voltage profile of load terminal decreases. Now we will study different cases for above IEEE 9-bus system.

CASE 1: IEEE 9-bus system without any compensation
CASE 2: IEEE 9-bus system with conventional PI controller based STATCOM
CASE 3: IEEE 9-bus system with Fuzzy Logic Controller based STATCOM
CASE 4: IEEE 9-bus system without any compensation with varying load
CASE 5: IEEE 9-bus system with conventional PI controller based STATCOM with varying load
CASE 6: IEEE 9-bus system with Fuzzy Logic Controller based STATCOM with varying load
CASE 7: IEEE 9-bus system without any compensation with three phase fault
CASE 8: IEEE 9-bus system with conventional PI controller based STATCOM with three phase fault
CASE 9: IEEE 9-bus system with Fuzzy Logic Controller based STATCOM with three phase fault

Now we will discuss all the cases in detail with the effect of using different controllers:

5.1 CASE 1: IEEE 9-bus system without any compensation

This is the case of an uncompensated IEEE 9-bus system.

As we can see in the above model, we are not using any device for compensation.

Fig 5.1 MATLAB/Simulink model of IEEE 9-bus system without any compensation

Fig 5.2 Simulink result of active and reactive power in phase A of IEEE 9-bus system without any compensation
Fig 5.2 shows active and reactive waveform v/s time graph. In this fig we can see that at the starting of simulation both waveform show some oscillation and after that it settles to a constant value which about $6.197 \times 10^7$ (for active power) and $1.4873 \times 10^7$ (for reactive power).

![Time Series Plot](image)

The above fig shows the voltage vs time graph. In the fig voltage starts increasing from zero time and it keep on increasing till its steady state value which is about 0.703 pu.

5.2 CASE 2: IEEE 9-bus system with conventional PI controller based STATCOM

To improve the voltage profile at the buses we use STATCOM as shunt compensator. This STATCOM is conventionally controlled using PI controller. For applying a device for compensation we must know the position where voltage sag will be maximum. In this bus system bus 3 is having maximum voltage sag, so we have applied STATCOM at 3rd bus.

![MATLAB/Simulink model](image)

Fig 5.4 MATLAB/Simulink model of IEEE IEEE 9-bus system with conventional PI controller based STATCOM
In the above fig we have used 6 IGBT to construct a 3 phase STATCOM. A battery is connected in parallel with STATCOM for providing switching power loss. Gate pulses for triggering of thyristor are fed from a pulse generator. A filter is also used to filter out the noise and harmonics. Output signal is fed to the corresponding bus where STATCOM is connected.

Above fig shows the model of pulse generator for STATCOM. In the above pulse generator we have used a PLL to separate frequency from the signal. Signal $V_{abc}$ is brought from the load bus A. This signal is fed to a difference block.
and compared with a reference signal to calculate the error. This error signal is controlled by a PI controller. A reference current signal and a current signal from load bus is fed to pulse generator which compares the two signals and generates gate pulses for IGBT.

The above graph clearly shows a distorted sinusoidal wave for active power and reactive power. The overall reactive power is increased after using STATCOM.

In the fig we can see that the voltage increases till its steady state value 0.78 pu. It takes 0.0166 sec to achieve steady state value. This fig clearly shows that the voltage profile is improved after using STATCOM.

5.3 CASE 3: IEEE 9-bus system with Fuzzy Logic Controller based STATCOM

To get the better result as compared to PI controller based STATCOM we use Fuzzy Logic Controller STATCOM. In the study we see that FLC based STATCOM provides better result as well it is more reliable in uncertain cases like varying loads and fault conditions. We’ll discuss these cases later on.
In the above fig we have used a fuzzy logic controller instead of conventional PI controller. There are two inputs of FLC and one output. This output is tuned by changing the gain and other parameters. The parameters are changed in such a way so that error signal is minimized. To get the desired result we must apply a rule base a system. Fig given below shows the rule base for FLC. Rule base is changed by hit and trial method to achieve the desired result.

### 5.3.1 Fuzzy Rule Base for this model:

<table>
<thead>
<tr>
<th>Error/Δerror</th>
<th>NB</th>
<th>NM</th>
<th>NS</th>
<th>Z</th>
<th>PS</th>
<th>PM</th>
<th>PB</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>NB</td>
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<td>NB</td>
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<td>Z</td>
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<td>NS</td>
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<td>Z</td>
<td>PS</td>
<td>PM</td>
<td>PB</td>
</tr>
<tr>
<td>PS</td>
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<td>Z</td>
<td>PS</td>
<td>PS</td>
<td>PM</td>
<td>PB</td>
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<tr>
<td>PB</td>
<td>Z</td>
<td>PS</td>
<td>PM</td>
<td>PB</td>
<td>PB</td>
<td>PB</td>
<td>PB</td>
</tr>
</tbody>
</table>

A triangular signal is used as membership function. Membership function shows relationship between input signal and output signal. It is like a mapping in math from input to output.
The diagram shows the active and reactive power waveform of phase A. Active power waveform is a pure sinusoidal which was distorted in case of PI controller. Thus active power waveform has been clearly improved after applying FLC in STATCOM for control purpose. Reactive power is also slightly increased in this case.

We can see that using FLC based STATCOM the voltage profile of the bus has been improved. The value of voltage bus is increased upto 0.9458 which was previously 0.9238 when we were using PI controller based STATCOM.
Now we check the reliability of above three cases i.e uncompensated, PI controller based STATCOM and FLC based STATCOM for varying load. We change the load as follows:

The load values as previous:

<table>
<thead>
<tr>
<th>Load</th>
<th>P-P rms voltage(V)</th>
<th>Active power</th>
<th>Reactive Power(VA)</th>
<th>Capacitive</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>230e3</td>
<td>70e6</td>
<td>30e6</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
<td>230e3</td>
<td>45e6</td>
<td>20e6</td>
<td>0</td>
</tr>
<tr>
<td>C</td>
<td>230e3</td>
<td>50e6</td>
<td>20e6</td>
<td>0</td>
</tr>
</tbody>
</table>

The changed values of the loads:

<table>
<thead>
<tr>
<th>Load</th>
<th>P-P rms voltage(V)</th>
<th>Active power</th>
<th>Reactive Power(VA)</th>
<th>Capacitive</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>230e3</td>
<td>70e6</td>
<td>70e6</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
<td>230e3</td>
<td>45e6</td>
<td>50e6</td>
<td>0</td>
</tr>
<tr>
<td>C</td>
<td>230e3</td>
<td>50e6</td>
<td>50e6</td>
<td>0</td>
</tr>
</tbody>
</table>

5.4 CASE 4: IEEE 9-bus system without any compensation with varying load

The main purpose of compensation is to increase the voltage profile at load terminal and to increase the reactive power demanded by the load. Whenever there is variation in load, reactive power demanded by the system also changes. So, to meet out the increased power demand we need a compensation device. In this case we observe the effect of load variation in the IEEE 9-bus system due to load variation. Load is increased as given in the table.

Fig 5.14 Simulink result of active and reactive power in phase A of IEEE 9-bus system without any compensation with varying load

Fig 5.15 Voltage v/s time plot of bus-1 of IEEE 9-bus system without any compensation with varying load
5.5 CASE 5: IEEE 9-bus system with conventional PI controller based STATCOM with varying load

![Fig 5.16 Simulink result of active and reactive power in phase A of IEEE 9-bus system with PI controller based STATCOM with varying load](image1)

In this case as we can observe from waveform that distortion is increased in active power wave due to increased load. Reactive power also drops from its previous value.

![Fig 5.17 Voltage v/s time plot of bus-1 of IEEE 9-bus system with PI controller based STATCOM with varying load](image2)

In varying the load, we have increased inductive demand, so due to this reactive power decreases in the system, which decreases the bus voltage since voltage is directly proportional to reactive power. In this case voltage is about 0.66 which is lesser than the previous value.

5.6 CASE 6: IEEE 9-bus system with Fuzzy Logic Controller based STATCOM with varying load

![Fig 5.18 Simulink result of active and reactive power in phase A of IEEE 9-bus system with FLC based STATCOM with varying load](image3)
Now in this case we will see the effect of applying FLC. Due to FLC, active power curve has become less distorted as from the previous case. There is also an improvement in reactive power from the PI controller. This case shows a reduction in reactive power from the case in which there was no load variation.

![Time Series Plot](image)

Fig 5.19 Voltage v/s time plot of bus-1 of IEEE 9-bus system with FLC based STATCOM with varying load

Cases of three phase fault:
To check the reliability of the system we check the system voltage, active and reactive power after applying three phase fault 0.0167 to 0.0833 seconds in each case i.e uncompensated, PI controller based STATCOM and FLC based STATCOM.

From this fig we can observe that the voltage profile is improved after using FLC. The point of steady state did not change. The load bus voltage is 0.88 pu which is less than the voltage which was achieved in last FLC case.

5.7 CASE 7: IEEE 9-bus system without any compensation with three phase fault

![Simulink result](image)

Fig 5.20 Simulink result of active and reactive power in phase A of IEEE 9-bus system without any compensation with three phase fault

In this case we have applied a three phase fault at bus no. 4 to observe the changes in voltage, active power and reactive power. The above fig shows that fault start at 0.017 sec and ends at 0.88 sec, during this interval active as well as reactive power drops to zero. And as fault is cleared at 0.88 sec active and reactive power gain its steady state value.

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Fig 5.21 Voltage v/s time plot of bus-1 of IEEE 9-bus system without any compensation with three phase fault

Similarly in case of reactive power voltage also drops to zero and then gains its steady state value. But in case of voltage, it takes some time to reach zero value. So voltage reaches zero value at 0.032 sec and reaches its steady state value at 0.83 sec.

5.8 CASE 8: IEEE 9-bus system with conventional PI controller based STATCOM with three phase fault

Fig 5.22 Simulink result of active and reactive power in phase A of IEEE 9-bus system with PI controller based STATCOM with three phase fault

Fig 5.23 Voltage v/s time plot of bus-1 of IEEE 9-bus system with PI controller based STATCOM with three phase fault

Overall voltage is improved after applying PI controller controlled STATCOM. But there is no change in voltage dip time duration.
In this case we have applied a PI controller based STATCOM for compensation purpose. As we can see that in this case when PI controller is used the active and reactive power does not drop to zero value. And we get an improved waveform for both active and reactive power.

5.9 CASE 9: IEEE 9-bus system with Fuzzy Logic Controller based STATCOM with three phase fault

When a fault occurs in a system where FLC based STATCOM is used, active and reactive power is very much improved. But it shows some oscillations at the beginning of the simulation. Reactive power is also improved. In this case reactive power rapidly attains its steady state value after the fault has been cleared.

5.10 OVERALL COMPARISON OF ALL THE THREE CASES:

<table>
<thead>
<tr>
<th>Case</th>
<th>Voltage (in p.u)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncompensated</td>
<td>0.7044</td>
</tr>
<tr>
<td>With pi controller</td>
<td>0.9238</td>
</tr>
<tr>
<td>With fuzzy logic controller</td>
<td>0.9458</td>
</tr>
</tbody>
</table>
VI. RESULT AND DISCUSSION

We have studied 9 different cases and compared the effects of STATCOM with PI controller and STATCOM with Fuzzy logic controller on bus voltage, reactive power and active power. The above cases we can easily understand that when we do not use any compensation device voltage profile at the load terminal is very poor, but after applying STATCOM it is improved to a operating value. Our study clearly shows that Fuzzy logic controller based STATCOM is much better that the PI controller based STATCOM controller. PI controller is a conventional controller and it is used to minimize error value the so that we can get better results. But there is one drawback of PI controller that, it can only be tuned for a particular loading. When there is change in load, we have to change the parameters of PI controller to achieve the desired result. As we can see that the Fuzzy logic controller is an adaptive controller; whenever there is change in loading or process parameters, it automatically changes its parameters according to changing process parameters. So there is no need of manual changes.

In the above result we have seen that voltage profile of bus-1 has been improved after using controllers with the uncompensated system. The value of voltage level of bus-1 is 0.7044p.u. in the uncompensated case. It has been improved to 0.9238p.u after using conventional PI controller based STATCOM. To get the better result with the influence of Fuzzy Logic Controller based STATCOM we achieved the voltage value at 0.9458p.u. Hence we conclude that Fuzzy logic controller is a better option to replace the conventional PI controller.

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