CHAPTER 4

STEADY STATE & DYNAMIC VOLTAGE STABILITY
ANALYSIS OF WIND FARMS WITH DFIG USING FACTS

4.1 VOLTAGE STABILITY DEFINITIONS

The concept of voltage stability addresses a different variety of issues depending on which the system being analyzed. Generally, voltage instability deals with dynamic loads and the means of loosing voltage control[2].

**Voltage Stability** is the ability of the power system to maintain steady voltages at all the buses in the system after being subjected to a disturbance. It is the ability of maintaining voltage, so that when load is increased, load power will also increase and voltage and power are controlled. It generally occurs in the form of a progressive fall or increase in voltages at some buses. The possible outcome when ever voltage instability occurs may cause tripping of transmission lines, loss of load in an area, tripping of other elements by their protective systems leading to cascading outages. Sometimes loss of synchronism also may occur[16]. **Voltage Collapse** is more complex than voltage instability and results in low voltage profile, voltage instability in a significant part of the power system. During any system contingencies there will be a huge demand for the reactive power to be supplied to the system, this additional demand will generally met by the reactive power reservegenerators and compensators. Using these reserves the sytem tries to settles to a stable voltage level. However, sometimes due to a combination of system conditions and events lack of additional reactive power may lead to voltage collapse causing a total or partial breakdown of the system. Normally in a stresses system voltage stability problems are more some times it may lead to voltage collapse which may be initiated by a variety of causes, the underlying problem is an inherent weakness in the power system[3].

The voltage stability definitions presented here are based on the IEEE/CIGRE [16]. It presents an overview of power system stability
The major factors because of which voltage collapses are:

- Limits in the value of Q and Voltage in the generator
- Characteristics of load
- Characteristics of VAR compensators (or) voltage control devices

**Large-Disturbance Voltage Stability:** This refers to the system's ability to maintain steady voltages following large disturbance such as system faults, loss of generation or circuit contingencies[15]. This ability is determined by the system and load characteristics, and the interactions of both continuous and discrete controls and protections[3]. By examining the nonlinear response of the system over a period of time to observe the performance and interactions of devices like motors, generator field current limiters, under load transformer tap changers large - disturbance voltage stability can be determined.

**Small - Disturbance Voltage Stability:** This refers to the system's ability to maintain steady voltages when subjected to small disturbances such as system load[2]. Characteristics of loads, discrete controls at a given instant of time and continuous controls influence this stability[3]. Small disturbance voltage stability analysis is helpful in determining the performance of the system for small system changes. The variation may vary from few seconds to ten minutes and so this voltage stability may be either short-term or long-term voltage stability.

**Short-Term Voltage Stability:** It involves dynamics of fast acting load components such as induction motors, electronically controlled loads and HVDC
converters[15]. This is similar to that of analysis of rotor angle stability. Dynamic modeling of loads is often essential and in addition to angle stability, short circuits near load are important.

**Long-Term Voltage Stability:** It involves slower acting equipment such as tap-changing transformer, generator current limiters and thermostatically controlled loads[2]. Since the study period of interest is up to minutes, long term simulations are required for the dynamic analysis[3]. Rather than the severity of the initial disturbance, stability is usually determined by the resulting outage of equipment.

### 4.2 IMPACTS OF WIND POWER ON VOLTAGE CONTROL

The development of wind power began in the year 1986 in India with its first station Ratnagiri in Maharasta, Okha in Gujarat and turticorn in Tamilnadu with 55KW vestas wind turbines. Table 4.1 shows that integration of significant penetration of wind power into the existing is not only possible but also often does not require a major redesign of the existing power system.

**Table 4.1: Wind power capacity in India**

<table>
<thead>
<tr>
<th>S.No</th>
<th>State</th>
<th>Capacity (MW) as of 31st March 2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Andhra Pradesh</td>
<td>1031.4</td>
</tr>
<tr>
<td>2.</td>
<td>Gujarat</td>
<td>3645.4</td>
</tr>
<tr>
<td>3.</td>
<td>Karnataka</td>
<td>2638.4</td>
</tr>
<tr>
<td>4.</td>
<td>Kerala</td>
<td>35.1</td>
</tr>
<tr>
<td>5.</td>
<td>Madhya Pradesh</td>
<td>879.7</td>
</tr>
<tr>
<td>6.</td>
<td>Maharashtra</td>
<td>4450.8</td>
</tr>
<tr>
<td>7.</td>
<td>Others</td>
<td>4.3</td>
</tr>
<tr>
<td>8.</td>
<td>Rajasthan</td>
<td>3307.2</td>
</tr>
<tr>
<td>9.</td>
<td>Tamilnadu</td>
<td>7455.2</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>23447.5</td>
</tr>
</tbody>
</table>

Generally, any power system engineer has to keep in mind that the main aim of the power system is to supply customers with good quality. If we introduce wind power into the power system the main aim will be fulfilled but the challenge in
introducing this power is related to its fluctuating nature of wind. The basic challenges are

a) To maintain acceptable voltage level at all buses

b) To maintain balance power.

In considering the system with Wind farms, impact of wind power on voltage control, must be distinguished between its impact on transmission networks and on distribution grids. In transmission networks, voltage control will be done in large scale power plants using synchronous generators by some dedicated equipment like capacitor banks, FACTS etc., These equipment also can be utilized even in distribution grids. The difficulties of wind energy integration into the existing system depends on

- Level of Integration of WECS
- Grid size
- Generation that is to be added into the grid.

Wind energy interconnection level can be managed upto 20% with the established control mechanisms and system reserves that are existing but for larger integration, some modifications in the existing network and their operating mode are required. The impacts of wind power are categorized as short and long term impacts. The short term effects are caused by the system balancing at operational time scale and the long term effects are related to its capability to meet peak load situations.

Local problems in the system will be with grid voltages i.e., quality problems near to the sites or steady state problems. When these plants incorporated at a wider range also affects power flow. At low penetration levels and at near load centers these effects are beneficial to the system. For example WPPs can support the system voltage during faults also they are capable of producing required reactive power support. Integration of wind power into the system may require additional upgrades in transmission and distribution grid infrastructure. It requires measure of regulating control depending on the level of penetration level and its characteristics. Sometimes wind energy production will be constrained because of the absence of some intelligent and managed systems where a combinational systems can cause wind power
production a constraint. But wind power plays a role in maintaining system stability and contributes to the security of supply.

4.3 MODELING & CONTROL OF FACTS DEVICES

FACTs stands for Flexible AC Transmission Systems is an evolving technology based solutions that help the industry to deal with changes in power related issues. The advantage of these devices is that they are widely recognized by the generation, transmission & distribution industries. The basic philosophy is to control power flows in transmission network by implementing power electronic controlled devices. Generally, WECS employs SCIG or DFIG or DDSG as its generator. These generators causes voltage drops at PCC as they draw reactive power from the main power grid. To solve these issues FACTS devices are being supported which provides required reactive power and supports the improvement in voltage regulation. Stability is the major aspect for introducing FACTS devices so today's research is majorly on employment of FACTS devices with respect to system stability and grid code requirements. In addition to this the major exercise is to achieve

- Transmission capabilities
- Voltage control
- Q recompense
- Power quality up gradation
- Power governing
- Quality of power enhancement
- Flicker elimination
- Interconnection of distributed generation.

Depending on the power electronic converter switches employed, the FACT devices are divided majorly into two categories [12]. They are:

1. Thyristor - based FACTs controllers
2. GTO- Based FACTS

Developments in high voltage power electronic devices have made practical apprehension of these devices. Before 1970s thyristor based devices have come into operation because of which the reply of passive components L & C has been
enhanced. But the control capabilities depends on the ratings of the components. The potential of transfer of a thyristor is a switch and so they cannot be used for incessant operation of the system. Later with the evolution of the latest technologies Gate Turn-Off based (GTO) FACTS have come into operation which designed SVC, TCSC, TCPAR. This has the characteristics of working for high voltage and currents. With this quality, improved rating of GTO made the use of Voltage sourced converters with shunt connection like STATCOM and used as series like SSSC. A UPFC can be utilized to control the parameters like impedance, voltage and phase angle. The various controllers that are used in wind generating system are SVC, STATCOM, UPFC, SSSC, TCSC, TC-PAR, IPFC, GUPFC, HPFC. The major requirement for a WECS is to have control over the reactive power at PCC, the shunt devices perform these functions. Thus this thesis proposed SVC and STATCOM for implementation in wind farm so that they remain connected continuously without instability problems.

4.3.1 Modelling Of SVC :

Static Var Compensators came into reality from early seventies and received promising importance of all the remaining devices. Fast control over the bus voltages can be achieved by using SVC with its conventional thyristor arrangement. They are shunt connected devices and are capable of captivating and producing the required reactive power. Having control over the L & C currents these devices are able to achieve voltage stability. There are various configurations like Thyristor controlled Reactor(TCR), Thyristor Switched Reactor(TSR), Thyristor switched Capacitor(TSC) or a combination of the three in parallel like FC-TCR, TSC-TCR and TCR-MSC [56]. Controlled reactors work based on controlling the firing angle of the thyristor where as in case of switched one L&C are included in the circuit in a step wise manner without having firing control. Generally these SVCs will be connected in a transmission line and so will have a design with more thyristor values in series and parallel combination which are adjusted with their conduction period so as to achieve voltage control capabilities.
In the case of FC-TCR as shown in fig 4.2(a), by varying firing angle of thyristor valve, current in reactor is controlled thus achieving variable reactive output over a wide range. During maximum VAR riveting, the TCR will be in full conduction so that net output will be based on reactor, capacitor, and filters whereas during maximum var production, the conduction of TCR will be off and the net output will be of capacitors and filters only.

In SVC with TSC-TCR combination as shown in fig 4.2(b), the output can be regulated through its entire range of operation. During the absorption period, TCR will be ON and TSC will be OFF so that the net out will be the difference between TCR and filters where as in the case of injection it will vice versa and the net output is sum of TSC’s and filters. With the configuration as shown in fig4.2(c), the output characteristics are same as that of case (b) but the major difference is its speed of operation and losses. The V-I characteristics are shown in fig 4.3 with a specific slope.

Fig 4.3 SVC V-I characteristics
Regulation slope is defined as
\[ \text{Slope} = \Delta V_{c_{\text{max}}} \]
\[ \text{slope} = \frac{\Delta V_{c_{\text{max}}}}{I_{c_{\text{max}}}} = \frac{\Delta V_{L_{\text{max}}}}{I_{L_{\text{max}}}} \]  \hspace{1cm} (4.1)

This slope allows the compensator operating range extension, voltage regulation loop stability, load sharing between SVC and other compensating devices. The reference voltage is defined as the point where SVC neither absorb or generate reactive power and this can be adjusted within typical range of ±10%. As the change in voltage is based on compensator current, the slope can be called as slope reactance \( X_{ls} \).

\[ V_r = V_{\text{ref}} + X_{ls} I_{\text{SVC}} \]  \hspace{1cm} (4.2)

From the characteristics, the control range of SVC is defined as
\[ I_{\text{min}} < I_{\text{sVC}} < I_{\text{max}} \]  \hspace{1cm} (4.3)
\[ V_{\text{min}} < V < V_{\text{max}} \]  \hspace{1cm} (4.4)

SVC is represented as \( jB \) which is defined as susceptance where \( B \) is defined as
\[ \text{if } V < V_{\text{min}} : B = \frac{1}{X_c} \quad \& \quad V > V_{\text{max}} : B = -\frac{1}{X_L} \]  \hspace{1cm} (4.5)

where \( X_c \) & \( X_L \) are called as the capacitive and inductive reactance's respectively.

During grid faults the current injection requirement is directly proportional to the voltage drop at the buses thus SVC must be capable of supplying required capacitive power which is a drawback of the system. Also, with thyristor valve arrangement the time taken for the response will be more and so the next generation of controllers came into existence.

**4.3.2 Modeling of STATCOM**

The furtherance of WECSs capacity is to generate or absorb reactive power can be done by going for the implementation of STATCOM and is a shunt connected device. By using this device either the voltage at the node or bus injected reactive power\( (Q) \) can be controlled. This device has one VSC with a DC link and one transformer with shunt connection\([57]\). The VSC consists of GTO based IGBT converter. Assuming a lossless connection then reactive power will be absorbed when current flows from grid to STATCOM else vice- versa. This will happen when the compensator voltage is lesser than the connection node voltage.
In the circuit a small DC capacitor is connected and so the device will be working for only Q exchange if it is replaced by an energy source, then the device will be capable of exchanging both P and Q. The purpose of the coupling transformer is that it connects the converter to the HV terminals and make certain that the DC capacitor is neither discharged fastly nor short circuited. Generally this device is used for regulation of voltage i.e., will reduce the over voltages during lightly loaded condition and will maintain level of the voltage during heavily loaded times. charging the DC capacitor and the losses due to switching operations will be done by the real power drawn by the converter. During steady operating condition, the real power(P) will be utilized by switching losses but as they are negligible, the output current of the device will be approximately 90° (lag) with respect to the terminal voltage as STATCOM is purely inductive in nature. In case of any disturbance, the device is capable of generating / absorbing reactive power.
Fig 4.4 (c) Current and Voltage representation

The characteristics of the device clearly explains that this device is capable of providing lead and lag compensation and also capable of controlling its output current within the L&C ranges whatever may be the system voltage even as low as 0.15 p.u. Thus it works for the necessary support in the system during and after fault otherwise the possibility of voltage collapse will happen. The maximum and minimum currents are represented by $I_{\text{Max}}$ and $I_{\text{Min}}$ respectively whereas the voltage in pu is represented $V_{\text{PU}}$. The switches of the converter will be naturally commuted for inductive var requirement whereas the maximum turnoff capability of the switches determines the transient current in the capacitive var region. In the generation mode, the capacitor starts charging on its own and in the other region vice-versa. This makes the converter voltages to lag behind the system voltage by some angle. Thus, the adjusting the converter output voltage, the generation and absorption of reactive power ($Q$) can be controlled.

The magnitude of current can be calculated for VAR generation as

$$I_{\text{ac}} = (V_{\text{out}}-V_{\text{ac}})/X$$  \hspace{1cm} (4.6)

The real power & reactive power transferred are given as

$$Q = (V_{2\text{out}}-V_{\text{out}}V_{\text{ac}}\cos(\alpha))/X$$  \hspace{1cm} (4.7)
The power production and absorption can be controlled independently if VSC can be connected to a another DC battery instead of DC link.

4.4 FUZZY LOGIC CONTROLLER

FLC is a fuzzy logic controlled system i.e., it is mathematical system that uses logic values between 0 and 1 for all the analog values. The major difference between digital inputs and this is that they take either discrete or takes values as '0' or '1' but here it is between 0 & 1. This technique is more applied for machine control. This technique was proposed by Lotif Zadeh in the year 1965 to process the imprecise data. The logic is implemented using crisp sets, true/false, Boolean etc. By using this accuracy in fractions and partial data also can be done. The term 'Fuzzy' explains us that the logic is expressed as either true or false instead partial true. Though there are other methods which perform similar to that of this such as genetic algorithm and neural network, but the advantage is that the solution will be in such a way that human operators will be able to understand so that they design the controller in easy manner[5]. Thus already human made control systems can be redefined easily using this logic.

Another advantages of this technique are

1. Easily they can be modified
2. Robust in nature
3. Multiple inputs and outputs can be used
4. Fast in response and economically feasible

4.4.1 Fuzzy Controller Design: Designing this controller requires more decisions pertaining to design than in the usual method pertaining to rules, interference engine, defuzzification method, data processing. While designing a fuzzy controller rules may be formed like

1. 'If error is -ve and Δe is -Ve then the output is 'NB'
2. 'If error is -ve and Δe is 0 then the output is 'NM'
The collection of such rules is called as 'Rule Base'. If the rules are in 'if-then' format, if side rules are called conditional rules and then side rules are called conclusion rules.

There are three types of fuzzy controllers they are

A. Direct control
B. Feed forward control
C. Adaptive control (Parameter)

In case of direct control method the controller will be in the direct path in a feedback system. The output is verified with a reference and based on the error, the controller works according to the strategy of the controller. In the case of feedforward control, a disturbance that can be measured is compensated. Fuzzy rules uses parameter adaptive control method so as to correct tuning parameters. In the operating point is suddenly changed in a non linear plant then the controller parameters can be changed according to the required operating point. This process is called as gain scheduling. Parameters of the sensors are also used for the measurement as scheduling variables used to change the controller table. Fig 4.5 shows a adaptive controller

![fig 4.5 Adaptive control Method]

**4.4.2 Fuzzy Controller Structure**: In order to support a design process, the fuzzy controller will have a specific characteristic procedure as shown in fig 4.6
In the preprocessing, measurements are conditioned before feeding into the controller[6]. For example

- Restrict the number of possible values in the samples
- To make agree with a single established value or standard range
- Removing disturbance by filtering
- Obtaining long or short term results by averaging the samples
- Discrete equilization and integrating or differentiation

After this the data will be passed into the controller.

4.4.3 Fuzzification: Fuzzification is the first block in the controller which is used to convert the input into several membership functions or one. Thus it matches the data with the rules to identify how much the conditions matches with the input given. For each linguistic there will be a degree of membership.

4.4.4 Rule Base: Several variables can be used in the rules either in if then or if side of the rules. Thus the controller can be used for MIMO or SISO systems. The controller requires 'e', 'Δe' and the accumulated error as inputs. While writing the rule base the names can be taken as Zero, pos,neg and these are the representations of the fuzzy sets as NB, NM, PB and PM. The member functions and rule viewer set is as in figure 4.7(a-b)
4.4.5 Interference Engine: A fuzzy interference system (FIS) uses set theory to map features (inputs) to classes (outputs). There are different types of FIS but two of them are used more in the theory. They are 1. SUGENO 2. MAMDANI

4.4.5.1 Sugeno Interference System: This is almost similar to that of the Mamdani system except that it does not have a membership function i.e., the step 4 in Mamdani FIS is not computed in this case. In this method the output is obtained by multiplying each input by a number and integrating all of them will give a crisp output. "Degree of applicability" is based on the rule strength and based on "Action" output is obtained. The distribution output will not be there only resulting action will be there which is a mathematical combination of action and applicability degree.
The major drawback in this method is that it doesn't have good instinctive method for finding the coefficients i.e., numbers that are pertaining to a particular class. Though it has some disadvantages, as Sugeno FIS is productive for certain algorithms so this method is used.

4.4.5.2 Mamdani Interference System

This is the generally observed methodology and is the first system built based on fuzzy sets in the year 1975 by Ebrahim Mamdani. The control logic was designed to control steam engine and the boiler by forming rules based on the inputs received from the human operators[60]. Fig 4.8(a) shows the 2-rule 2- input membership function and fig 4.8 (b) shows the rule implemented in the present thesis. The process is based on the following procedure

1. Framing rule base
2. Using membership functions the inputs must be fuzzified
3. To establish rule strength based on rule base and the fuzzified inputs
4. By combining the strength of the rule and membership function the consequences of the rule should be identified
5. Based on that the distribution output to be obtained
6. The distributed output to be defuzzified.

Fig: 4.8(a) 2- rule 2- input Mamdani system with a fuzzy input

Fig 4.8(b) Mamdani implemented in STATCOM Circuit
4.4.6 Defuzzification

The process of converting the fuzzy set into a number so as to send it as a control signal to the process is called Defuzzification. The result will be a crisp set of signals. There are several methods of defuzzification. They are 1. Centre of gravity (COG) 2. Centre of gravity method for singletons (COGS) 3. Bisector of area (BOA) 4. Mean of maxima (MOM) 5. Left most maximum (LM) & Right most maximum (RM).

4.4.7 Post Processing: In this process the output defined on standard universe will be scaled to engineering units like volts, amps etc. this unit will have gain to which the output to be tuned and as also an integrator.

Thus when using a fuzzy controller the following points are to be kept in mind
- Rule based related outputs like number of inputs & outputs, rules, mimo/siso, membership functions
- Interference engine
- Identifying method of defuzzification
- Pre and post processing

Based on PID controller the fuzzy controller can be used in the procedure of the design in this manner
- PID controller to be tuned
- Replacing it with fuzzy sets
- Determining the transfer gains
- Making the fuzzy controller a nonlinear one
- Fine tuning the controller.

The controllers implemented in SVC & STATCOM are as shown in fig 4.9(a-b) and 4.10(a-b) without and with fuzzy controller.
Fig 4.9 (a) SVC controller without Fuzzy Controller

Fig 4.9(b) Fuzzy controller implemented in SVC
Fig 4.10(a) STATCOM current regulator model without Fuzzy Controller

Fig 4.10(b) Fuzzy controller Implemented in STATCOM
4.5 STEADY STATE VOLTAGE STABILITY ANALYSIS OF A 4 BUS TEST SYSTEM

The four bus test system considered for analysis is as shown in figure 4.11(a) under steady operating conditions. Steady state voltage stability is the ability of the system to maintain voltages under normal operating condition. Generally voltage stability is identified by computing the voltages and phase angles at all the buses using load flow analysis. Hence other methods such as V-P curve analysis, Q-V modal curves, V-Q sensitive analysis etc., may be applied for voltage stability studies. Enhancement of voltage and maintenance at all buses indicates that the system is maintaining stability. The analysis is carried out using Matlab/Simulink.

4.5.1 Simulation of the 4 Bus Test Systems with Base Case

In order to analyze this a four bus system is considered with base case and with wind energy as a source. Fig 4.11(a) shows the base case. This is to measure the performance of the system itself, without consideration of any controllers. The data is as presented in Appendix A.
Fig 4.11(b) shows the system with wind energy under simulation without FACTS controllers

### 4.5.2 Simulation of the 4 Bus Test Systems with Wind Energy

The voltages, real and reactive power under base and with wind energy are as shown in 4.2

<table>
<thead>
<tr>
<th>Buses</th>
<th>Voltages</th>
<th>Base Case (pu)</th>
<th>With wind energy (pu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>V₁</td>
<td>0.8037</td>
<td>0.8766</td>
</tr>
<tr>
<td>2</td>
<td>V₂</td>
<td>0.8368</td>
<td>0.8962</td>
</tr>
<tr>
<td>3</td>
<td>V₃</td>
<td>0.8037</td>
<td>0.8766</td>
</tr>
<tr>
<td>4</td>
<td>V₄</td>
<td>0.8037</td>
<td>0.8519</td>
</tr>
</tbody>
</table>

4.2 Voltages at all buses & its comparison

From the above 4.2 it is observed that using wind energy also the voltages can be increased and in order to maintain them at 1 pu it is required to have a reactive power generating devices like SVC or STATCOM. The system with wind energy under steady operating conditions is shown in fig4.11(b)

The Test system consists of two wind farms each of capacity 1.5MW connected to 120KV grid via transmission line of 25KV, 30Km feeder. This system supplies to a load of 5MW, 3MVAR. The WT uses DFIG and an AC/DC/AC IGBT PWM converter. The rotor through a converter is fed with variable frequency and the stator winding will be directly connected to the 50HZ grid. By using the DFIG
technology maximum energy can be extracted even at lower wind speeds. The major edge of DFIG is its capability to generate/absorb reactive power by using power electronic converters thereby avoiding additional compensating capacitors unlike SCIG.

Under steady operating conditions, the bus B4 is near the wind farm, and B2 near the grid.

![Fig 4.12 P & Q at bus B4 under steady condition](image)

From the fig4.12 it is observed that the real power(P) generated at bus B4 i.e., near the wind farm is 3MW, the reactive power(Q) is maintained at almost 0MVAR.

![Fig 4.13(a) shows the voltage at bus B4 maintained stable](image)
Fig 4.13(b) shows the voltages at all buses maintained stable.

Fig 4.13(c) Real power (P) and reactive power (Q) at bus B1
4.6 DYNAMIC VOLTAGE STABILITY ANALYSIS OF THE 4 BUS TEST SYSTEM

4.6.1 Simulation Without Controller

Fig. 4.14 System under dynamic condition without controller

Fig. 4.14 shows the system with sudden variation in load i.e., the system subjected to sudden disturbance at time $t=1$ sec during such disturbance the powers and voltages at all buses gets disturbed and because of which the system loses its...
stability. Fig 4.15 (a) shows the variation in voltages and powers during this disturbance.

Fig 4.15(a) Voltages at all buses during dynamic condition

At time $t=1$ sec when sudden load change has occurred the voltages at all the buses falls below a level. Fig 4.15(b) shows the voltage at bus B4 where we can observe dip in the voltage at time $t = 1$ sec.

Fig 4.15(b) Voltage at bus B4 during disturbance at time $t = 1$ Sec
4.6.2 Simulation with SVC & Fuzzy based SVC as its controllers

Though the system did not lose its synchronism but is unable to regain the voltages at all buses after the load variation. Thus implementation of FACTS controllers will make the system to regain.

4.16(a) System Under dynamic condition with SVC

The above system is implemented with Static Var compensator (SVC) at time \( t = 2 \) sec. Fig 4.16(a) represents the system with SVC controller and fig 4.16(b) shows the variation in voltage at bus B4 and also the powers exchanged at all the buses.
In order to achieve the response at a faster rate, fuzzy logic controller is implemented with a rule set of 49. The time taken by the response is less when compared to that of SVC without fuzzy.

Fig4.16 (c-f) shows the power variations at all buses with and without controller.

4.16(c) P and Q at bus B1 with SVC and Fuzzy SVC

4.16(d) P and Q at bus B2 with SVC and Fuzzy SVC
4.16(e) P and Q at bus B3 with SVC and Fuzzy SVC

4.16(f) P and Q at bus B4 with SVC and Fuzzy SVC

From the above results it is observed that the time taken to get the response using fuzzy rule set is higher than with SVC. The below table 4.3(a-c) shows the real power (P) and reactive power (Q) consumed at the various buses during disturbance and after clearing the disturbance using SVC as its controller.
Table 4.3(a) Comparison of Real Powers all buses Without, With & Fuzzy based SVC

<table>
<thead>
<tr>
<th></th>
<th>Without SVC</th>
<th>With SVC</th>
<th>With Fuzzy SVC</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1(MW)</td>
<td>5.817</td>
<td>6.392</td>
<td>6.949</td>
</tr>
<tr>
<td>P2(MW)</td>
<td>2.881</td>
<td>3.348</td>
<td>3.482</td>
</tr>
<tr>
<td>P3(MW)</td>
<td>2.716</td>
<td>3.192</td>
<td>3.323</td>
</tr>
<tr>
<td>P4(MW)</td>
<td>2.654</td>
<td>2.897</td>
<td>2.957</td>
</tr>
</tbody>
</table>

Table 4.3(b) Comparison of Reactive Powers all buses Without, With & Fuzzy based SVC

<table>
<thead>
<tr>
<th></th>
<th>Without SVC</th>
<th>With SVC</th>
<th>With Fuzzy SVC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q1(MVAR)</td>
<td>2.493</td>
<td>2.739</td>
<td>2.786</td>
</tr>
<tr>
<td>Q2(MVAR)</td>
<td>2.317</td>
<td>0.7898</td>
<td>0.5011</td>
</tr>
<tr>
<td>Q3(MVAR)</td>
<td>2.024</td>
<td>0.5402</td>
<td>0.2423</td>
</tr>
<tr>
<td>Q4(MVAR)</td>
<td>0.5291</td>
<td>1.982</td>
<td>2.282</td>
</tr>
</tbody>
</table>

Table 4.3(c) Comparison of Voltages all buses Without, With & Fuzzy based SVC

<table>
<thead>
<tr>
<th></th>
<th>Without SVC</th>
<th>With SVC</th>
<th>With Fuzzy SVC</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1(pu)</td>
<td><strong>0.9026</strong></td>
<td>0.9439</td>
<td><strong>0.9475</strong></td>
</tr>
<tr>
<td>V2(pu)</td>
<td><strong>0.8531</strong></td>
<td>0.8673</td>
<td><strong>0.8688</strong></td>
</tr>
<tr>
<td>V3(pu)</td>
<td><strong>0.9026</strong></td>
<td>0.9439</td>
<td><strong>0.9475</strong></td>
</tr>
<tr>
<td>V4(pu)</td>
<td><strong>0.9045</strong></td>
<td>0.9524</td>
<td><strong>0.9505</strong></td>
</tr>
</tbody>
</table>
4.6.3 Simulation with STATCOM & Fuzzy based STATCOM as its controller

From the 4.3 (a-c) it is observed that though SVC is capable of enhancing the voltage of the system at all buses in comparison with out controller. But there is a requirement for the voltages to be more enhanced at the buses so the next controller STATCOM is been introduced in the system at PCC. Fig4.17(a) shows the circuit employed with STATCOM at PCC. The voltage response is shown in fig 4.17(b)

![Diagram](image)

Fig 4.17 (a) System under dynamic condition with STATCOM

![Graph](image)

Fig 4.17(b). Voltage variation at bus B4 near the WG
In order to achieve faster response the PID controller in the STATCOM is replaced with Fuzzy controller. Fig 4.17(c) shows the variation in voltage at bus B4 using Fuzzy

![Voltage Variation Graph](image)

Fig 4.17(c) shows B4 Voltage with fuzzy STATCOM

The real and reactive power flow at all the buses from B1 to B4 with STATCOM and Fuzzy based STATCOM is shown in fig 4.17(d-g)

![Power Flow Graph](image)

4.17(d) P and Q at bus B1 with STATCOM and Fuzzy STATCOM
4.17(e) P and Q at bus B2 with STATCOM and Fuzzy STATCOM

4.17(f) P and Q at bus B3 with STATCOM and Fuzzy STATCOM
4.17(g) P and Q at bus B4 with STATCOM and Fuzzy STATCOM

The working of the STATCOM at time t= 2 sec is as shown in figure 4.17(h)

4.17(h) P and Q at STATCOM bus

The corresponding real powers, reactive powers and voltages at all buses with Statcom and Fuzzy Statcom are presented in the below table 4.4(a-c)
Table 4.4(a) Comparison of Real Powers all buses Without, With & Fuzzy based STATCOM

<table>
<thead>
<tr>
<th></th>
<th>Without Controller</th>
<th>With STATCOM</th>
<th>With Fuzzy STATCOM</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1(MW)</td>
<td>5.817</td>
<td>6.949</td>
<td>6.657</td>
</tr>
<tr>
<td>P2(MW)</td>
<td>2.881</td>
<td>3.482</td>
<td>3.551</td>
</tr>
<tr>
<td>P3(MW)</td>
<td>2.716</td>
<td>3.323</td>
<td>3.391</td>
</tr>
<tr>
<td>P4(MW)</td>
<td>2.654</td>
<td>2.891</td>
<td>2.912</td>
</tr>
</tbody>
</table>

Table 4.4(b) Comparison of Reactive Powers all buses Without, With & Fuzzy based STATCOM

<table>
<thead>
<tr>
<th></th>
<th>Without Controller</th>
<th>With STATCOM</th>
<th>With Fuzzy STATCOM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q1(MVAr)</td>
<td>2.493</td>
<td>2.815</td>
<td>2.818</td>
</tr>
<tr>
<td>Q2(MVAr)</td>
<td>2.317</td>
<td>0.3213</td>
<td>0.3293</td>
</tr>
<tr>
<td>Q3(MVAr)</td>
<td>2.024</td>
<td>0.058</td>
<td>0.06591</td>
</tr>
<tr>
<td>Q4(MVAr)</td>
<td>0.5291</td>
<td>2.852</td>
<td>2.847</td>
</tr>
</tbody>
</table>

Table 4.4(c) Comparison of Voltages all buses Without, With & Fuzzy based SVC

<table>
<thead>
<tr>
<th></th>
<th>Without Controller</th>
<th>With STATCOM</th>
<th>With Fuzzy STATCOM</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1(pu)</td>
<td><strong>0.9026</strong></td>
<td>0.9513</td>
<td>0.993</td>
</tr>
<tr>
<td>V2(pu)</td>
<td><strong>0.8531</strong></td>
<td>0.8817</td>
<td>0.906</td>
</tr>
<tr>
<td>V3(pu)</td>
<td><strong>0.9026</strong></td>
<td>0.9513</td>
<td>0.993</td>
</tr>
<tr>
<td>V4(pu)</td>
<td><strong>0.9045</strong></td>
<td>0.9801</td>
<td>0.996</td>
</tr>
</tbody>
</table>
From the table 4.4(c) it is observed that voltage can be better enhanced if the system is employed with Fuzzy based STATCOM. The table 4.5 show comparison between voltages at all buses with the different controllers.

Table 4.5 Comparison between voltages with different FACTS Devices

<table>
<thead>
<tr>
<th></th>
<th>Without controller</th>
<th>With SVC</th>
<th>With Fuzzy SVC</th>
<th>With STATCOM</th>
<th>With Fuzzy STATCOM</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1(pu)</td>
<td>0.9026</td>
<td>0.9439</td>
<td>0.9475</td>
<td>0.9513</td>
<td>0.993</td>
</tr>
<tr>
<td>V2(pu)</td>
<td>0.8531</td>
<td>0.8673</td>
<td>0.8688</td>
<td>0.8817</td>
<td>0.906</td>
</tr>
<tr>
<td>V3(pu)</td>
<td>0.9026</td>
<td>0.9439</td>
<td>0.9475</td>
<td>0.9513</td>
<td>0.993</td>
</tr>
<tr>
<td>V4(pu)</td>
<td>0.9045</td>
<td>0.9524</td>
<td>0.9505</td>
<td>0.9801</td>
<td>0.998</td>
</tr>
</tbody>
</table>

From the bar chart shown in fig 4.18( it is observed that during dynamic operating condition the voltage stability can be maintained using FACTS devices especially with Fuzzy based STATCOM.

**Fig 4.17(i) shows Voltage variations**
4.7 DYNAMIC STABILITY ANALYSIS OF IEEE 9 BUS SYSTEM

Results shown above prove that stability intensification will be done by implementing STATCOM with fuzzy controller in a grid connected system with wind farm as its source. In order to justify the results an IEEE 9 bus system as shown in fig. 4.18

Fig 4.18 IEEE 9 bus system

The single line diagram shown in figure is also called as WSCC (Western System Coordinating Council) 3 machine 9 bus system. This is also otherwise called as the P.M.Anderson system. This system consists of three(03) generators, six(06)transmission lines, three(03) loads and three (03) two winding transformers. As
the analysis is on implementation of the FACTS devices in a WECS, two generators are considered as wind generators with a capacity of 150MW each at 0.9Pf. The wind power consists of 100 units each amounting to 1.5MW generating at a voltage of 575V, 50HZ. The three loads connected are Load A at bus 5 with a capacity of 125MW, 50MVAr, Load B at bus B6 with a load capacity of 90 MW, 30MVAr and the other load C at bus 8 with a capacity of 100MW, 35 MVAr. The wind generators are connected at buses B3 and B2 whereas bus B1 is connected with a conventional generator and this is considered as the slack (ref) bus. The other two buses i.e., B2 & B3 are considered as PV buses with rest buses as PQ buses. The load buses are connected to a voltage of 230KV by means of three two winding transformers rated at 230KV/575V, 262MVA. The transmission line parameters and bus data is as shown in Appendix B

The above system is observed for voltage variations at all the buses and it is identified that the buses near the wind farm are maintaining good voltage profiles as shown in table 4.6.

<table>
<thead>
<tr>
<th></th>
<th>V1</th>
<th>V2</th>
<th>V3</th>
<th>V4</th>
<th>V5</th>
<th>V6</th>
<th>V7</th>
<th>V8</th>
<th>V9</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1</td>
<td>0.9469</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V2</td>
<td></td>
<td>0.994</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V3</td>
<td></td>
<td>0.9963</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V4</td>
<td></td>
<td></td>
<td>0.9469</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V5</td>
<td></td>
<td></td>
<td></td>
<td>0.9371</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.9475</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.9863</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.976</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.9914</td>
<td></td>
</tr>
</tbody>
</table>

In order to observe the impact of STATCOM in a grid connected WECS, during any load disturbance, a sudden load change of 125MW of 50MVAr is observed near load A during time t = 10s to t = 13 sec. 4.19(a) shows the system implemented with sudden load change, Fig 4.19 (b) shows voltage variations at all buses without any controller.
Fig 4.19 (a) System subjected to sudden load change at bus B5

Fig 4.19 (b) Voltage at all 9 buses without any change in load & Controller
Table 4.7 Dynamic condition without controller

<table>
<thead>
<tr>
<th>( V_1 )</th>
<th>( V_2 )</th>
<th>( V_3 )</th>
<th>( V_4 )</th>
<th>( V_5 )</th>
<th>( V_6 )</th>
<th>( V_7 )</th>
<th>( V_8 )</th>
<th>( V_9 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8292</td>
<td>0.9109</td>
<td>0.9189</td>
<td>\textbf{0.8292}</td>
<td>\textbf{0.8294}</td>
<td>0.8388</td>
<td>0.8955</td>
<td>0.8876</td>
<td>0.9036</td>
</tr>
</tbody>
</table>

4.7.1 With STATCOM as its Controller

From the table 4.7 the bus voltage B4 and B5 are affected much because of sudden change near the load A. A STATCOM incorporated at bus B5 will enhance these voltages. Fig 4.8 (b) shows the single line diagram with STATCOM.

Fig 4.20(a) System implemented with STATCOM at bus B5.
Table 4.8 shows the voltages at all the 9 buses with STATCOM implemented in the circuit.

<table>
<thead>
<tr>
<th></th>
<th>$V_1$</th>
<th>$V_2$</th>
<th>$V_3$</th>
<th>$V_4$</th>
<th>$V_5$</th>
<th>$V_6$</th>
<th>$V_7$</th>
<th>$V_8$</th>
<th>$V_9$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without STATCOM</td>
<td>0.8292</td>
<td>0.9109</td>
<td>0.9189</td>
<td><strong>0.8292</strong></td>
<td><strong>0.8294</strong></td>
<td>0.8388</td>
<td>0.8955</td>
<td>0.8876</td>
<td>0.9036</td>
</tr>
<tr>
<td>With STATCOM</td>
<td>0.9736</td>
<td>0.9993</td>
<td>0.9992</td>
<td><strong>0.9736</strong></td>
<td><strong>0.9832</strong></td>
<td>0.9668</td>
<td>0.9998</td>
<td>0.9854</td>
<td>0.9979</td>
</tr>
</tbody>
</table>

Table 4.8 Voltages at 9 buses during dynamic condition with STATCOM as its controller

![Voltage at Bus B5 with and without STATCOM](image)

**Fig 4.21(a)** Voltage at bus B5 with and without STATCOM

Corresponding real and reactive powers at load buses A, B & C is as shown in figures 4.21 (b-d)
Fig 4.21 (b) P & Q near Load A with & without STATCOM

Fig 4.21 (c) P & Q near Load B with & without STATCOM
Fig 4.21 (d) P & Q near Load C with & without STATCOM

4.7.2 With Fuzzy Based STATCOM as its Controller

As discussed in the section 4.6.3, fuzzy based statcom will provide better and faster results. Thus implementing the fuzzy rule set for the statcom in the defined multi machine system, the corresponding voltages are shown in table as 4.9.

<table>
<thead>
<tr>
<th></th>
<th>$V_1$</th>
<th>$V_2$</th>
<th>$V_3$</th>
<th>$V_4$</th>
<th>$V_5$</th>
<th>$V_6$</th>
<th>$V_7$</th>
<th>$V_8$</th>
<th>$V_9$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without STATCOM</td>
<td>0.8292</td>
<td>0.9109</td>
<td>0.9189</td>
<td><strong>0.8292</strong></td>
<td><strong>0.8294</strong></td>
<td>0.8388</td>
<td>0.8955</td>
<td>0.8876</td>
<td>0.9036</td>
</tr>
<tr>
<td>With STATCOM</td>
<td>0.9736</td>
<td>0.9993</td>
<td>0.9992</td>
<td><strong>0.9736</strong></td>
<td><strong>0.9832</strong></td>
<td>0.9668</td>
<td>0.9992</td>
<td>0.9854</td>
<td>0.9979</td>
</tr>
<tr>
<td>With fuzzy STATCOM</td>
<td>0.9819</td>
<td>0.9998</td>
<td>0.9998</td>
<td><strong>0.9819</strong></td>
<td><strong>0.998</strong></td>
<td>0.9729</td>
<td>0.9998</td>
<td>0.9885</td>
<td>0.9989</td>
</tr>
</tbody>
</table>

Table 4.9 Comparison between all the controllers
Fig 4.22 (a) Voltage at bus B5 with Statcom and Fuzzy Statcom

From the fig 4.22(a) and table 4.10 it is observed that by implementing the fuzzy controller the voltages at buses B4 and B5 got improved and voltages also maintained at 1pu. The statcom control circuit implemented with fuzzy controller is as shown in figure 4.22(b)

Fig 4.22 (b) STATCOM circuit implemented with fuzzy logic controller in 9 bus system
As explained in 3.3.2 the rotor speed ($\omega_r$) is maintained at 1.2pu and $V_{dc}$ at 1200V with pitch angle $\beta$ at 0° as shown in figure 4.23.

![Figure 4.23](image)

Fig 4.23 $\omega_r$, $\beta$ and $V_{dc}$ during dynamic condition

![Figure 4.24 (a)](image)

Fig 4.24 (a) Power variations at LOAD A with Statcom and Fuzzy Statcom
Fig 4.24 (b) Power variations at LOAD B with Statcom and Fuzzy Statcom

Fig 4.24 (c) Power variations at LOAD C with Statcom and Fuzzy Statcom
Figures 4.24(a-c) shows the contrast in real power $(P)$ and reactive power $(Q)$ during dynamic period at all the load buses Load A,B,C respectively.

4.7 CONCLUSIONS

The Voltage profiles during dynamic operating condition in a grid connected WECS is enhanced by implementing the FACTS devices. From the results thus obtained form a 4 bus test system, it is observed that voltage stability i.e., enhancing the voltage profiles can be achieved by implementing STATCOM as its controller with implemented Fuzzy logic controller instead of the classical PID controller. The identified FACTS device improved the profiles in an IEEE 9 bus system.